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EFFECTS OF ENERGETIC PARTICLE EVENTS ON VLF/LF PROPAGATION PARA--ETC(U)
MAR 82 J P TURTLE, J E RASMUSSEN
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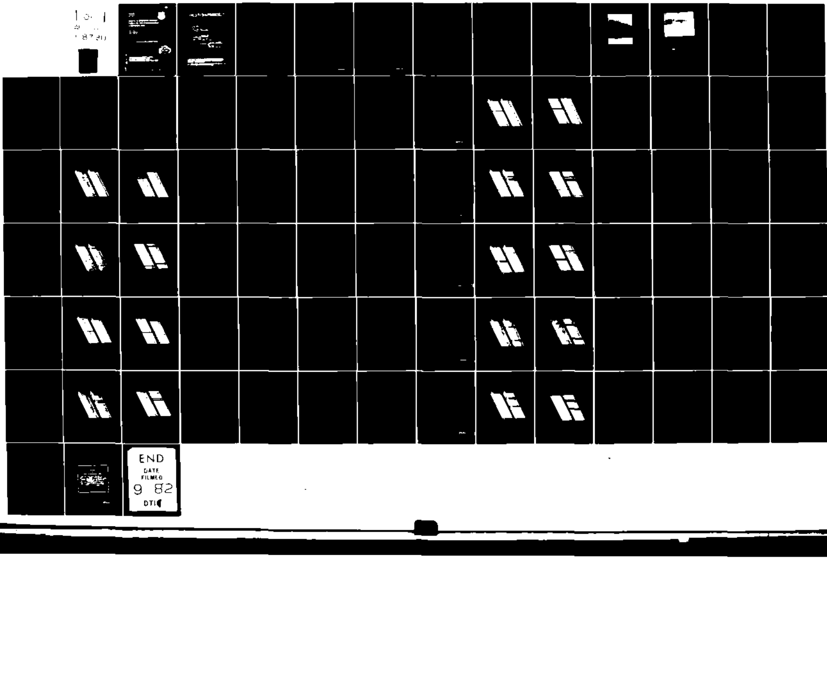

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This report provides a summary of disturbance effects of energetic particle events on VLF/LF propagation parameters as observed by the USAF High Resolution VLF/LF Ionosounder in northern Greenland. Disturbance effects on ionospheric reflectivity parameters, including reflection heights and coefficients, are presented along with data from a riometer, a magnetometer, and satellite particle detectors.

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Preface

The authors thank Royce C. Kahler and Duane Marshall for help with the instrumentation which made the measurements possible, and Jens Ostergaard and Bjarne Ebbesen for the outstanding operation in Qanaq, Greenland.

Appreciation is also extended to the Danish Commission for Scientific Research in Greenland for allowing these measurements to be conducted and to Jorgen Taagholt, the Danish Scientific Liaison Officer for Greenland and to V. Neble Jensen of the Geophysics Division of the Danish Meteorological Institute for their continued cooperation.

Contents

Illustrations

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Effects of Energetic Particle Events on VLF/LF Propagation Parameters/1979

1. INTRODUCTION

A compilation of data on the VLF/LF reflectivity of the polar ionosphere during 1979 has been published in previous technical reports.[1-3] In this report, the data for specific periods are expanded to give a more detailed presentation of the effects of energetic particle events on VLF/LF propagation parameters. These periods have been chosen to show disturbance effects for events in which the differential 13.7 to 25.2 MeV proton flux recorded by the IMP 7/8 satellites exceeded 10^{-2} particles/cm^{2}sec-sec-sr-MeV. The propagation data were obtained by the USAF High Resolution VLF/LF Ionosounder[4,5] which provides direct measurements of ionospheric reflection height and the reflection coefficient matrix elements $_{\parallel}R_{\parallel}$ and $_{\parallel}R_{\perp}$.[6] Also included are data on particle flux density, 30 MHz riometer absorption, and geomagnetic field intensity.

The VLF/LF Ionosounding Transmitter (Figure 1) is located at Thule Air Base Greenland (76° 33' N Lat., 68° 40' W Long.), and the receiving site is 106 km north at the Danish Meteorological Institute's Ionospheric Observatory in Qanaq, Greenland (77° 24' N Lat., 69° 20' W Long.), Geomagnetic Lat. (89° 06' N). The ionosounding transmissions consist of a series of extremely short (approximately

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(Due to the large number of references cited above, they will not be listed here. See References, page 93.)

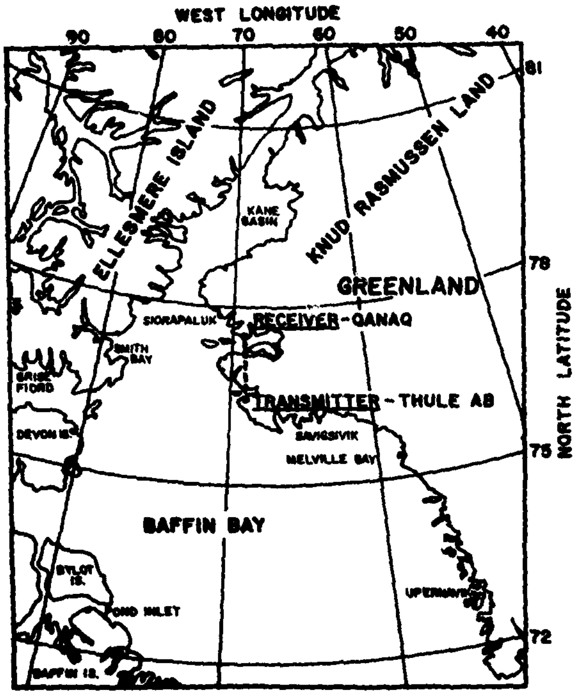

Figure 1. Ionosounder Propagation Path, Thule AB—Qanaq, Greenland

100 μsec) VLF pulses, precisely controlled in time, and radiated from the 130-m vertical antenna (Figure 2a). Orthogonal loop antennas (Figure 2b) are used to receive the two polarization components of the ionospherically reflected skywave signal. One loop, oriented in the plane of propagation, senses the groundwave and the unconverted or "parallel" (‖) component of the down-coming skywave; the second loop, nulled on the groundwave, senses the converted or perpendicular (⊥) skywave component. The signal from each of the antennas is digitally averaged to improve the signal-to-noise ratio of the individual received waveforms. The average then is recorded on magnetic tape. At the receiver, the radiated signal arrives first by groundwave propagation (Figure 3). Due to the extremely short pulse length, the groundwave has passed the receiver before the arrival of the ionospherically reflected skywave pulse, providing independent groundwave and skywave data. An example of the observed waveforms is given in Figure 4, where the parallel waveform (a) consists of a groundwave propagated pulse, a quiet interval containing low level, off-path groundwave reflections, followed by the first-hop parallel skywave component; the perpendicular waveform (b) is also shown. Each of these waveforms

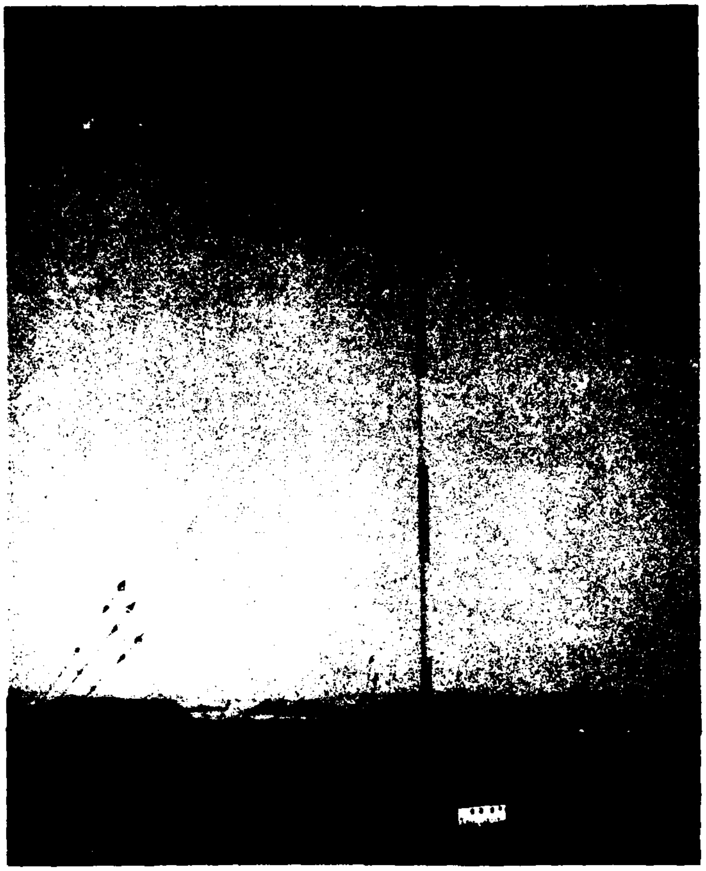

Figure 2a. Transmitting Antenna—Thule AB, Greenland

is comprised of 256 digitally averaged points, spaced 2 μsec apart. Ionospheric reflection parameters are derived by computer processing of the ground and ionospherically reflected waveforms, with allowance made for factors such as ground conductivity and antenna patterns (see Section 2.2).

Figure 5 shows the Fourier amplitude spectrum of the received groundwave signal. Although the data presented are generally limited to frequencies in the first, or principal lobe of the spectrum, information at higher frequencies can be used when sufficient signal-to-noise conditions exist. There is, however, a frequency range around each spectral null where insufficient signal exists for measurements.

Figure 2b. Orthogonal Receiving Antennas—Qanaq, Greenland

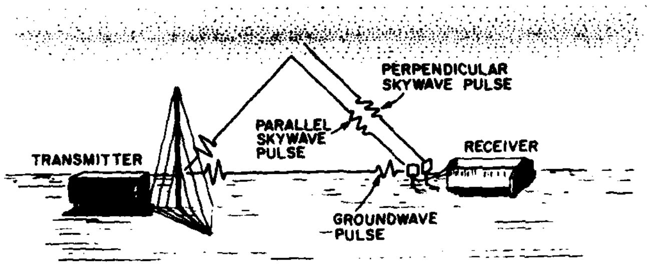

Figure 3. Basic Ionosounding Experiment

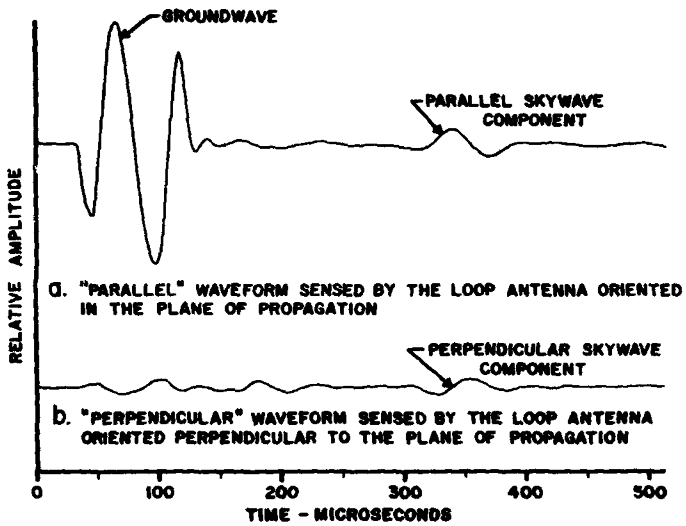

Figure 4. Example of Parallel and Perpendicular Waveforms

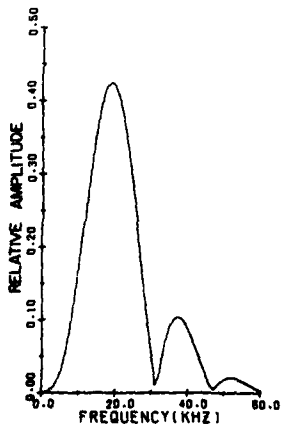

Figure 5. Fourier Amplitude Spectrum of Transmitted Pulses

2. EVENT DATA

The data are presented for each disturbance event in three general formats: first, the observed waveforms are shown in a synthetic three-dimensional display which starts approximately 2 days prior to the event and covers a 14-day period; second, the data are presented in the frequency domain with reflection heights and

coefficients plotted as a function of frequency over the range from approximately 5 to 30 kHz; third, the data are presented as a function of time-of-day. In addition to reflection information, this section contains data on ionospheric absorption, geomagnetic field activity, and solar proton fluxes.

2.1 Observed Waveforms

A three-dimensional waveform display is presented for a 2-week period containing each disturbance event, together with a display of the same 2-week period from a year in which it was not disturbed. For each display, the waveforms were stacked one behind the other in linear time, progressing from bottom to top. Each individual waveform is a 30-min average of approximately 650,000 pulses. The horizontal scale for these plots is linear in time (microseconds), measured from the start of the groundwave. This scale can be used to calculate an effective height of reflection by attributing the time delay between the start of the groundwave and the start of the skywave to a difference in travel distance, assuming a sharply bounded, mirror-like ionosphere. Figure 6 gives a conversion curve for this calculation based on simple geometry and the specific Thule AB—Qanaq, Greenland, separation of 106 km. For the disturbance periods, fixed local ground clutter, amounting to only 2% of the groundwave amplitude, was removed by computer processing to avoid interference with the skywave and improve the appearance of the waveforms.

The three-dimensional displays of the disturbed and normal parallel waveforms are given for each event in Parts A and B of Figures 8 through 16. A plot of the diurnal variation in solar zenith angle for the midpoint of the path appears in Part C. The perpendicular waveform displays are shown in Parts D and E. The time of maximum particle flux is indicated on the "disturbed" plots.

2.2 Quantitative Reflection Parameters

For each event individual parallel and perpendicular waveforms were selected to show the effects of the disturbance on the ionospheric reflection height and reflection coefficients as a function of frequency. The selected waveforms from the disturbance period are shown in Part F of the data figures, whereas the corresponding undisturbed waveforms are shown in Part G.

2.2.1 REFLECTION HEIGHTS

The group mirror height (GMH) of reflection was obtained by determining the group delay of the skywave relative to the groundwave and attributing this difference to a difference in the propagation distance. The group delay can be defined as the rate of change of phase with frequency as discussed in Lewis et al.[4] For the

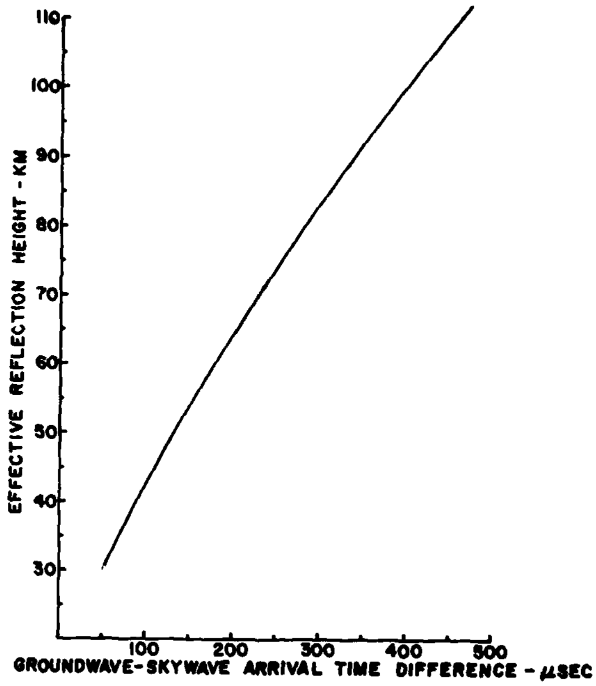

Figure 6. Conversion Curve Groundwave—Skywave Arrival Time Difference to Reflection Height

GMH data presented in this report, a finite frequency difference of 1.0 kHz was used, and the corresponding phase difference as a function of frequency for the groundwave and both skywave signals was obtained by Fourier analysis of the respective pulses. The GMH calculations took into account ground conductivity (10^{-3} mho/m is assumed), with the Wait and Howe[7] corrections applied. Group mirror heights for the parallel and perpendicular waveforms are plotted as a function of frequency in Parts H and I of Figures 8 through 16 for both normal and disturbed conditions. The GMH's are also presented as a function of time-of-day for the average frequency of 16.5 kHz. In Figures 8 through 16, Parts L and O, parallel and perpendicular reflection height information is given based on two-hour averaged data for the two-week period; Parts V and W show the 24-hour period of the event onset in greater detail, based on 5-min averaged data. These parts

7. Wait, J. R., and Howe, H. H. (1956) Amplitude and Phase Curves for Groundwave Propagation in the Band 200 Cycles per Second to 500 Kilocycles, Nat'l Bureau of Standards, U.S. Circ. No. 574.

include a normal reflection height curve for reference purposes. Each point of the reference height curve is an average, by 2-hour time blocks, for the 14-day normal period indicated.

2.2.2 REFLECTION COEFFICIENTS

Assuming that the ionosphere acts as a "mirror" at the GMH, we obtained plane wave reflection coefficients[7] by comparing the ratio of the skywave Fourier amplitude at a specific frequency to that of the groundwave, taking into account the wave spreading, earth curvature, ground conductivity, path lengths, and antenna patterns including ground image effects.

The reflection coefficient ${}_{\parallel}R_{\parallel}$, obtained from analysis of the parallel skywave component, is plotted as a function of frequency for both normal and disturbed conditions in Part H. From the corresponding perpendicular skywave pulses, the coefficient ${}_{\parallel}R_{\perp}$ was obtained; it appears as a function of frequency in Part I. The ${}_{\parallel}R_{\parallel}$ coefficient for 16 kHz is plotted as a function of time-of-day in Part M along with the averaged normal coefficient. As with the reflection heights, a more detailed ${}_{\parallel}R_{\parallel}$ coefficient plot, based on 5-min averaged data, is shown in Part V. To show the variation in reflectivity as a function of frequency during the event, the reflection coefficients were calculated at 8 kHz, 16 kHz, and 22 kHz and are plotted in Part N as a function of time for the 14-day period. The corresponding reflection coefficient plots for ${}_{\parallel}R_{\perp}$ are given in Parts, P, Q, and W.

For certain coefficient data points, plotted as asterisks, the reflection coefficient appears without a corresponding GMH. For these particular data, only the skywave-groundwave ratios could be obtained since the skywaves were too weak to provide reliable group delay information. The reflection coefficients were estimated, therefore, using a nominal GMH of 80 km in the calculations. These estimated coefficient values are included in the averages presented in Parts M, N, P and Q, but the assumed heights are not used in the GMH averages.

2.3 Polarization Ellipses for the Down-Coming Skywaves

As described by Rasmussen et al,[8] the polarization ellipse of the skywave can be determined from the amplitudes of the parallel and perpendicular components and their phase difference. Each ellipse represents the locus of the tip of the rotation field vector as seen when looking in the direction of propagation of the down-coming skywave, with the x-axes being horizontal. The ellipses are drawn to a scale in which the incident wave amplitude is unity, and each division on the axis is 0.1. The direction of rotation is indicated by an arrow. Parts J and K of

8. Rasmussen, J.E., et al (1975) Low Frequency Wave-Reflection Properties of the Equatorial Ionosphere, AFCRL-TR-75-0615, AD A025111.

Figures 8 through 16 present polarization ellipse data as a function of frequency at 5 kHz intervals based on the selected disturbed and normal waveforms of Parts F and G, respectively.

3. SUPPLEMENTARY DATA

In order to interpret the effects of ionospheric disturbances on the VLF/LF ionosounding data, information from several geophysical sensors are included. Parts R and S of Figures 8 through 16 present data from a 30 MHz riometer and a magnetometer operated by RADC at Thule AB, Greenland. The riometer, the conventional monitor of ionospheric disturbances, measures the signal level of cosmic noise passing through the ionosphere. A decrease in the received noise level results from increased absorption caused by enhanced ionization from energetic particles. The riometer data in this report have been normalized to remove the quiet day curve. The data plotted in Part R of each figure give riometer absorption levels. A zero level represents normal undisturbed conditions, a positive deflection shows increased absorption while a negative deflection results from a noise increase as would be associated with a solar radio burst. The effects of energetic particle events are seen as an increase in the absorption level followed by a gradual recovery to normal levels over a period of several days. The magnetometer data plotted are the horizontal (H) component of the polar magnetic field determined by a three-axis fluxgate magnetometer at Thule AB. The magnetometer responds to the effects of polar ionosphere current systems related to disturbance events.

In addition to the information from the ground-based monitors, particle flux data are presented from the Applied Physics Laboratory of Johns Hopkins University experiments aboard the IMP 7 and 8 satellites.* These satellites are in roughly circular orbits at about 35 earth radii. The data presented in Parts T and U are hourly averages of differential flux levels for protons in two energy ranges: 0.97 to 1.85 MeV and 13.7 to 25.2 MeV. These particle data are most important for relating the VLF/LF ionosounder effects to the size of a particular disturbance.

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*Particle data obtained from the National Space Science Data Center, Greenbelt, Maryland.

4. DISTURBANCE CHARACTERISTICS

Table 1 gives a summary of the data presented for each event covered in this report. In addition, data are included for 22 events which occurred from 1974-1978. These events were described in previous reports.[9,10]

During 1979, eight energetic particle events occurred for which the 13-25 MeV proton flux was greater than $10^{-2}/cm^2$ sec sr MeV. The effects of these events on the ionosounding waveforms are given in this report (Figures 8-14). Also included are two other events (Figures 15 and 16) which had large numbers of 1 MeV protons but less than 10^{-2} 13-25 MeV protons (below the event criterion for this report). The magnitude of the disturbance on the VLF/LF propagation parameters is a function of the proton flux and the solar illumination conditions during the event.

The drop in reflection heights for both parallel and perpendicular components coincides with the influx of energetic particles. Data relating 16 kHz parallel reflection heights and particle flux levels from Table 1 are plotted in Figure 7. The numbered points in the figure are 1979 events, and the other points are events from the previous years listed in Table 1. In the plot the maximum 13-25 MeV differential proton flux is plotted as a function of the lowest reflection height recorded during the event. As all of the events in this report had some amount of solar illumination, the lowest reflection heights generally occurred around local noon when the reflection heights represent a combination of particle and solar ionization. In Figure 7 the lines labelled "day" and "night" are best fit curves to the data for the two illumination conditions for events prior to 1979. The 1979 points follow the same height-flux relation seen in previous events.

The typical response of both the parallel and perpendicular reflection heights to the ionization caused by energetic particles alone is a sudden drop followed by a gradual return to normal levels over several days, roughly following the particle flux curve. Superimposed on this pattern is a sinusoidal variation, the amplitude of which is a function of the solar zenith angle. In winter, during the polar night, there is no variation due to the lack of solar radiation in the D-region. In the polar summer, during continuous daylight conditions, there is also no diurnal height

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9. Turtle, J.P., Rasmussen, J.E., Klemetti, W.I. (1980) Effects of Energetic Particle Events on VLF/LF Propagation Parameters, 1974-1977, RADC-TR-80-307, AD A104508.

10. Turtle, J.P., Rasmussen, J.E., Klemetti, W.I. (1981) Effects of Energetic Particle Events on VLF/LF Propagation Parameters, 1978, RADC-TR-81-82, AD A103945.

Table 1. Solar Particle Events

Event Date	Figure 7 Point No.	Maximum 13.7-25.2 MeV Proton Flux (cm^2 sec sr MeV)	Minimum 16 kHz ‖ Reflection Height (km)	30 MHz Riometer Absorption (dB)	Illumination Conditions
1979 Events					
2 Mar (061)	8	0.15	63	< 0.5	day-night
3 Apr (093)	9	0.2	61	2	day-night
6 Jun (157)	10	20.0	58	6	daytime
1 Aug (213)	11	0.035	70	< 0.5	daytime
19 Aug (231)	12	20.0	57	4	daytime
8 Sept (251)	13	0.1	63	0.5	daytime
15 Sept (258)	14	3.0	58	2	day-night
16 Nov (320)	15	3.0	62	1	day-night
1978 Events [10]					
13 Feb (044)		60.0	56	6.0	day-night
25 Feb (056)		0.05	64	< 0.5	day-night
7 Mar (066)		0.02	70	< 0.5	day-night
8 Apr (098)		0.1	65	< 0.5	day-night
11 Apr (101)		3.0	58	3.0	daytime
17 Apr (107)		0.2	60	0.5	daytime
28 Apr (118)		no data	no data	9.8	daytime
7 May (127)		10.0	57	1.0	daytime
11 May (131)		0.1	63	< 0.5	daytime
31 May (151)		0.4	63	1.0	daytime
11 July (192)		0.3	64	1.0	daytime
8 Sept (251)		0.18	63	< 0.5	day-night
23 Sept (266)		100.0	51	10.0	day-night
8 Oct (281)		0.8	65	< 0.5	day-night
10 Nov (314)		0.3	65	1.0	day-night
12 Dec (345)		0.1	74	< 0.5	nighttime
1974-1977 Events [9]					
5 Nov 74 (309)		1.3	63	< 0.5	day-night
30 Apr 76 (121)		6.0	58	3.0	daytime
22 Aug 76 (235)		0.6	60	1.7	daytime
26 Jul 77 (207)		0.02	70	< 0.5	daytime
24 Sept 77 (267)		2.0	57	2.0	day-night
22 Nov 77 (326)		14.0	64	0.75	nighttime

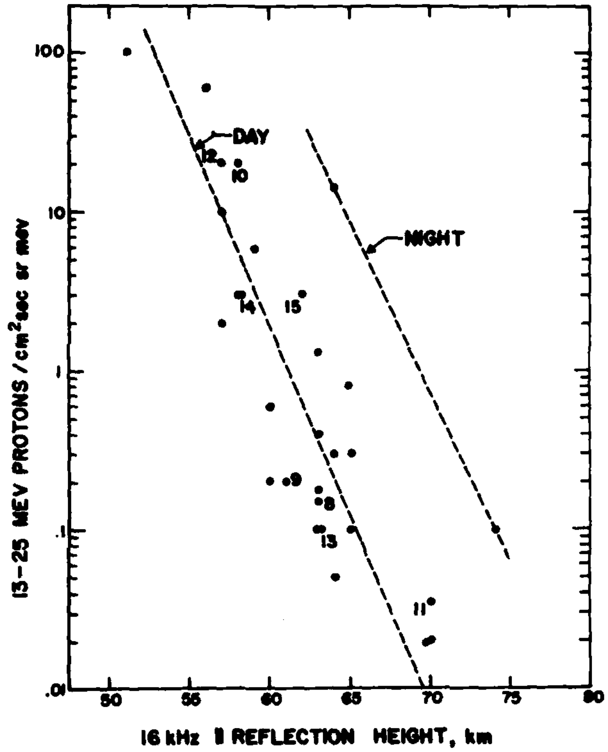


Figure 7. 13.7 - 25.2 MeV Proton Flux vs the Minimum 16 kHz$_{||}$ Reflection Height

variation during an event even though one is seen before and after the event. In the presence of energetic particle ionization, the height of electron density level at which the ionosounding waves are reflected is not affected by solar zenith angle variations for angles less than 90°. The 6 June event (Figure 10) is typical of a daytime event. In the day-night conditions encountered around March and September, diurnal height variations are seen during the disturbances. The amplitude of these variations can be stronger than seen before or after the event. The 2 March event (Figure 8) is typical of day-night disturbance events. Because the solar illumination conditions are changing very rapidly in March and September, the amplitude and day to night ratio of the diurnal variation change from week to week. Because of these variations no one model can be used for this day/night period.

The effects of energetic particles on the reflection coefficients are somewhat more complex. During nighttime events the reflection coefficients show a small decrease with a gradual recovery, similar to the reflection heights. During polar daytime events the parallel reflection coefficients actually increase at event onset. This is followed by a gradual decrease as the event recovers. This increase is not seen in the perpendicular coefficients. Near the end of the recovery period both of the 22 kHz coefficients typically go through a null. This could be evidence of interference between reflections from two reflecting layers formed during the event. During day-night events the interaction between rapidly changing solar UV-ionization and particle ionization produces a more complex disturbance pattern.

2 March 1979 Solar Proton Event

DAY	061
Report Figure:	8
Related Solar Flare:	No flare identified
Start of Ionospheric Disturbance:	1100 UT
Time of Maximum 13-25 MeV Proton Flux:	3 March 0800 UT
Maximum Flux:	0.15 particle/cm^2 sec sr MeV
Length of Particle Event:	8 Days
Lowest 16 kHz Reflection Height:	63 km
30 MHz Riometer Absorption:	< 0.5 dB
Solar Zenith Angle Range:	84° - 112°
Illumination Conditions:	Day-night

This event occurred during a time when the sun was above and below the horizon at the latitude of Thule AB. The effects of this disturbance are seen as a characteristic decrease in reflection heights and coefficients followed by a gradual recovery. During the event the magnitude of the variation of diurnal reflection heights (parts L&O) and coefficient (parts N&Q) is greater than seen in undisturbed conditions. This is due to the combined effects of particle ionization and varying amounts of solar illumination. The magnitude of the effect on the reflection coefficients increases with increasing frequency. Before the reflection parameters returned to normal levels a second, smaller event occurred beginning on 10 March (DAY 069). The event lasted until about 20 March (DAY 079).

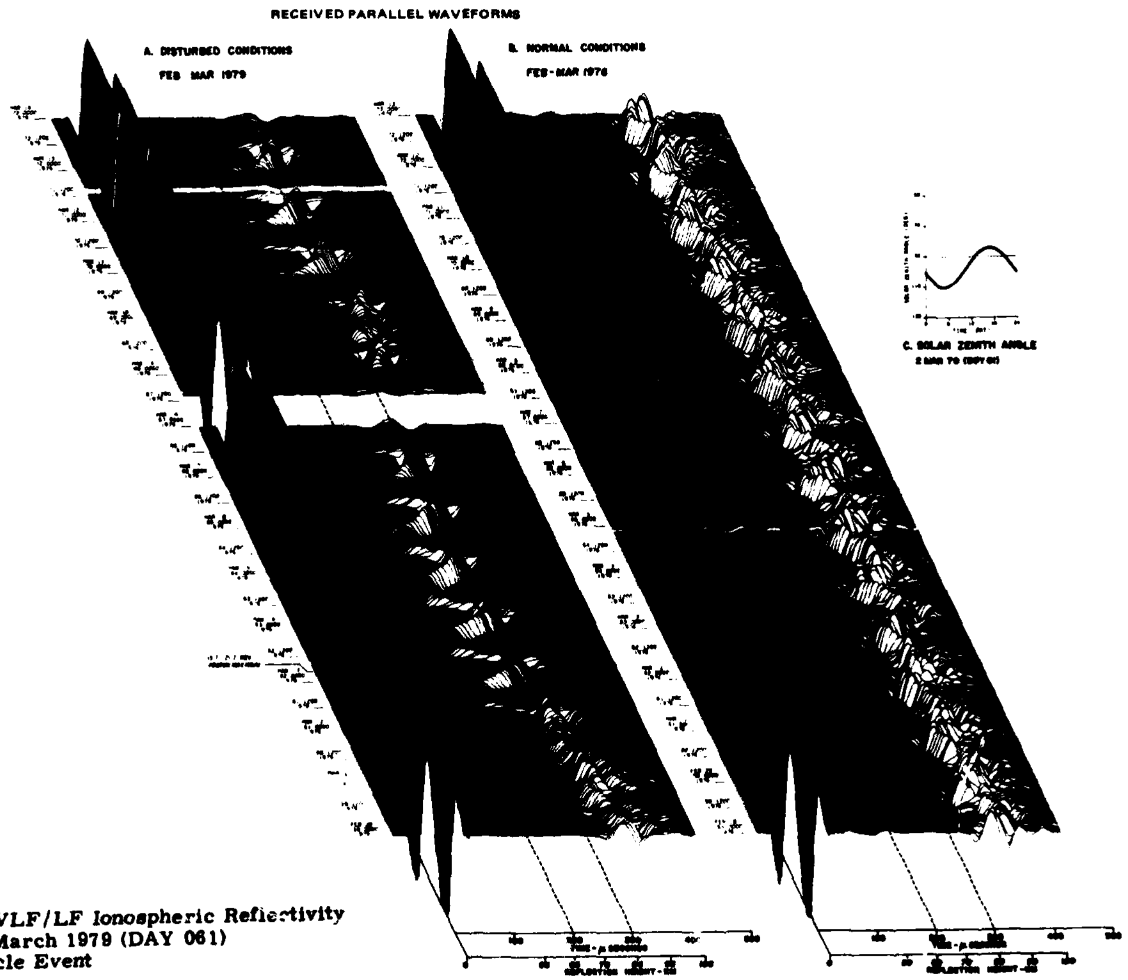


Figure 8. VLF/LF Ionospheric Reflectivity Data for 2 March 1979 (DAY 061) Solar Particle Event

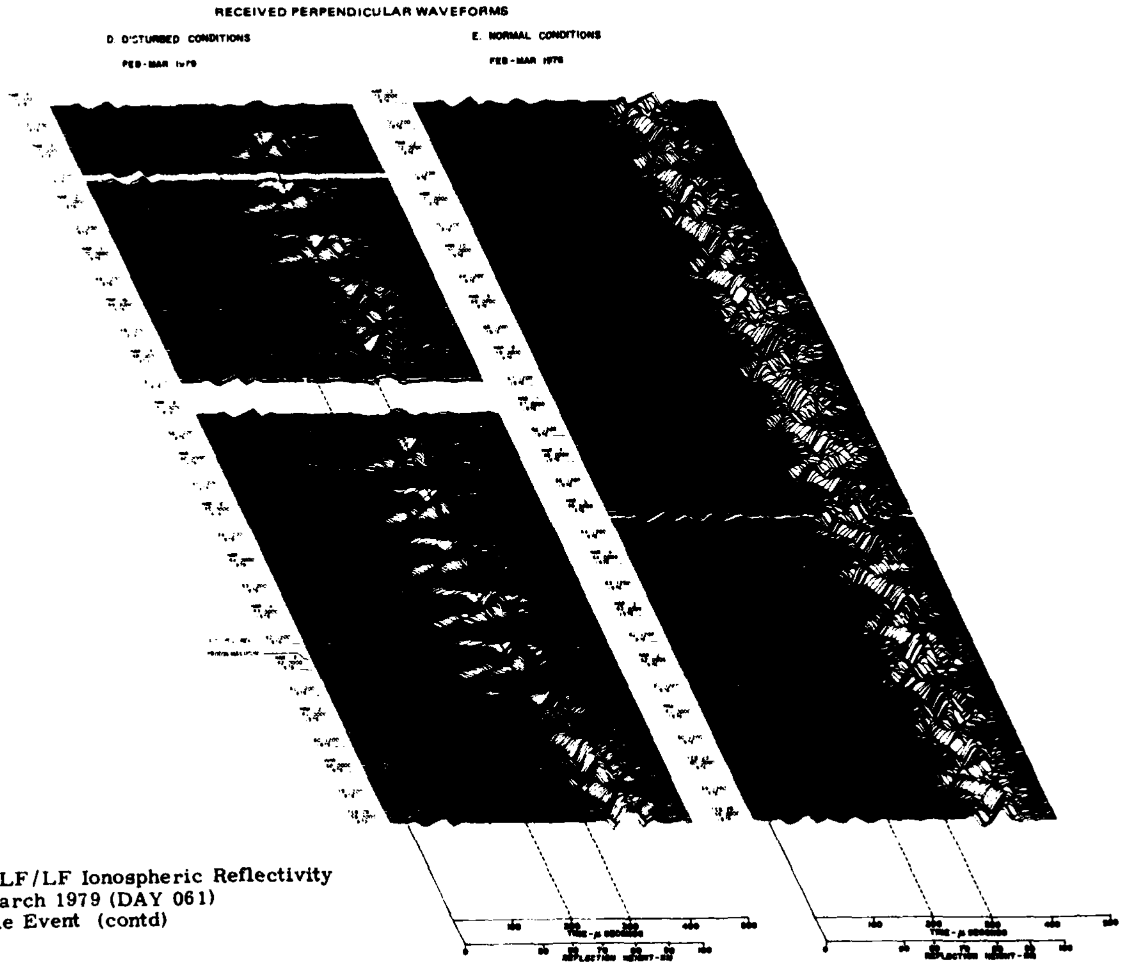


Figure 8. VLF/LF Ionospheric Reflectivity Data for 2 March 1979 (DAY 061) Solar Particle Event (contd)

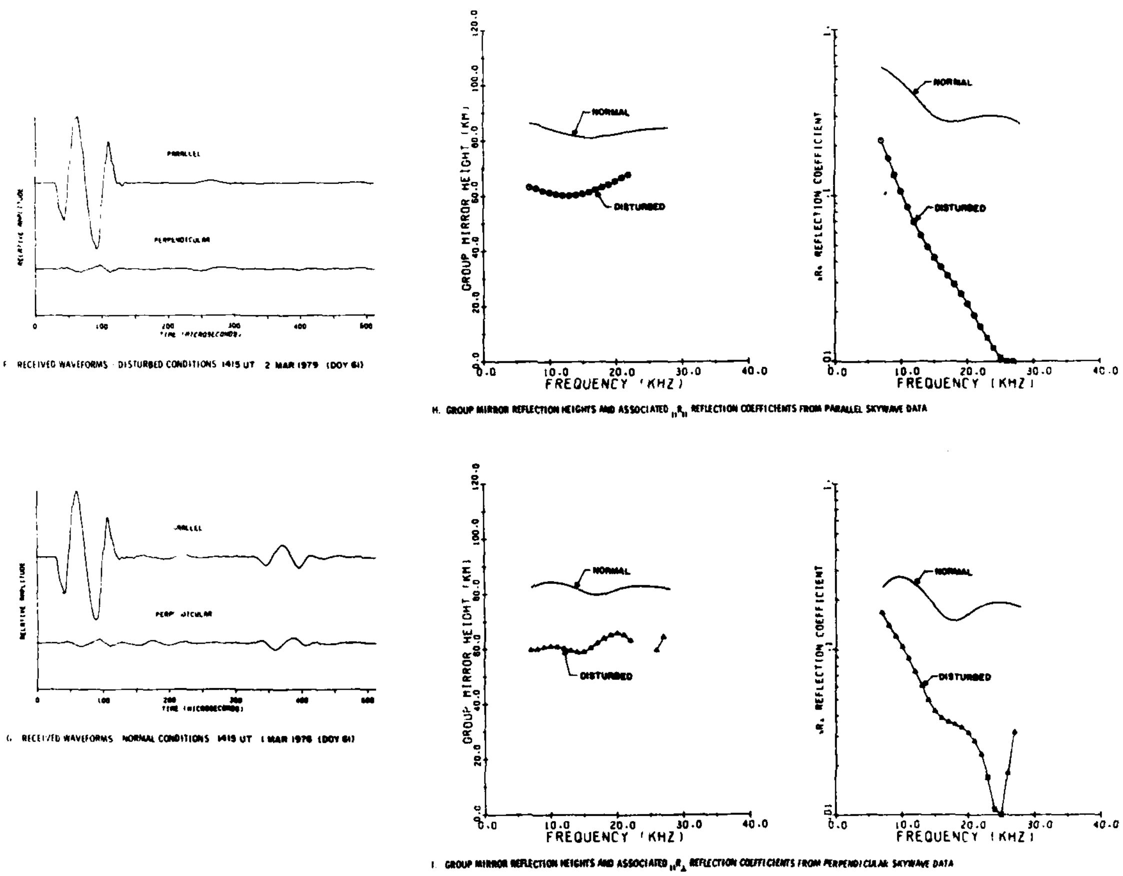
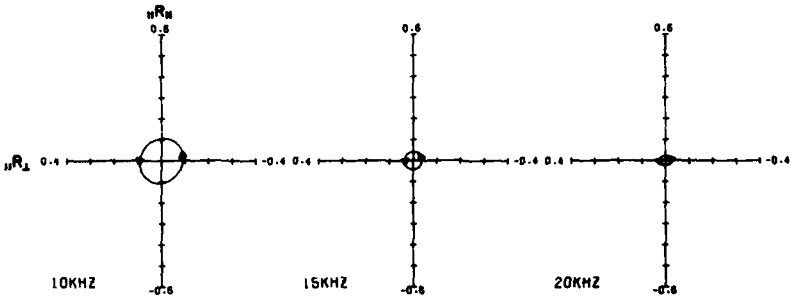
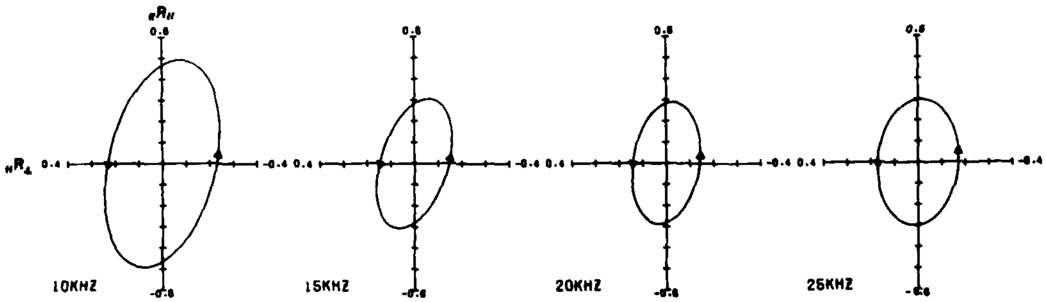


Figure 8. VLF/LF Ionospheric Reflectivity Data for 2 March 1979 (DAY 061) Solar Particle Event (contd)



J. SKYWAVE POLARIZATION ELLIPSES - DISTURBED CONDITIONS



K. SKYWAVE POLARIZATION ELLIPSES - NORMAL CONDITIONS

Figure 8. VLF/LF Ionospheric Reflectivity Data for 2 March 1979 (DAY 061) Solar Particle Event (contd)

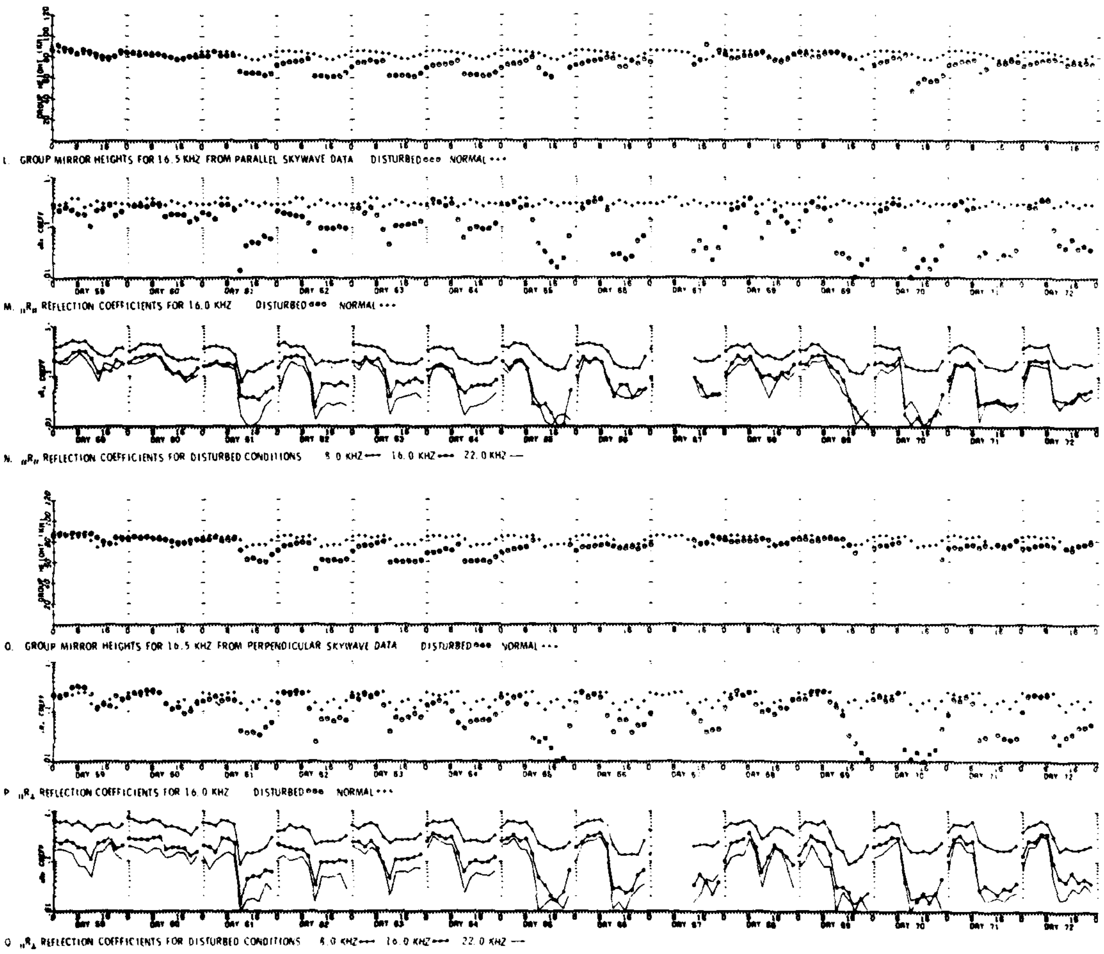


Figure 8. VLF/LF Ionospheric Reflectivity Data for 2 March 1979 (DAY 061) Solar Particle Event (contd)

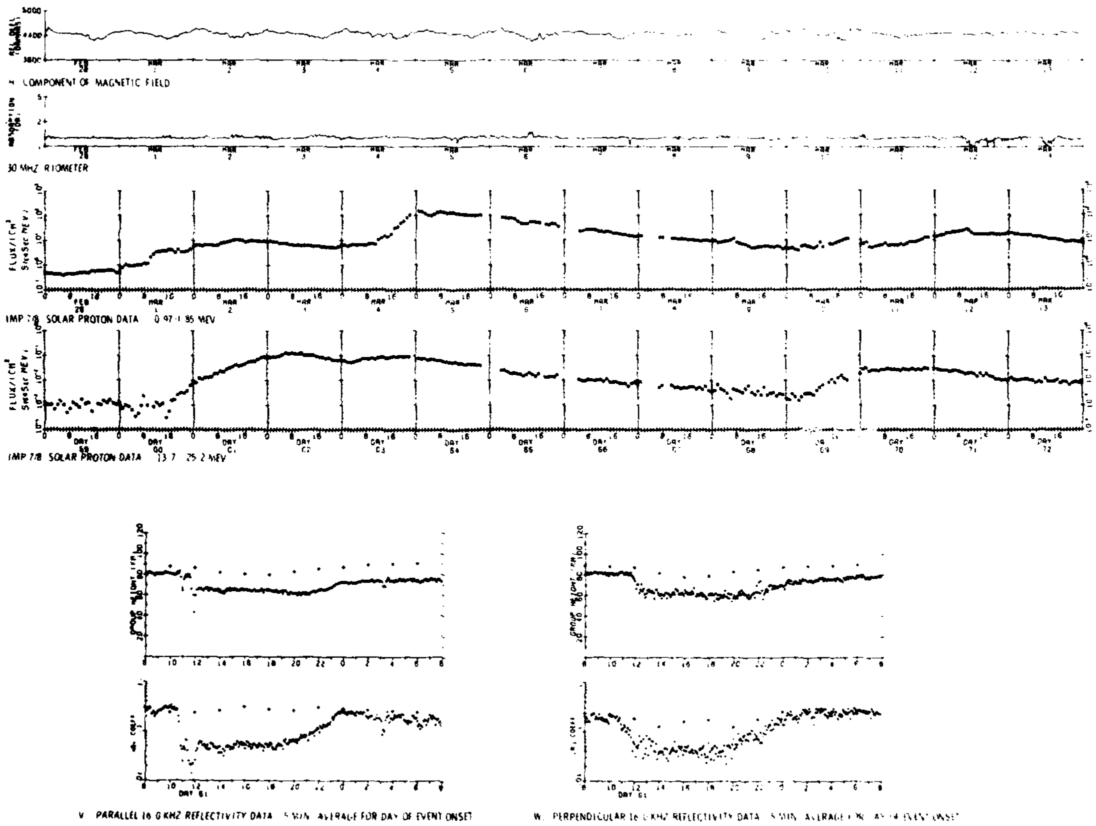


Figure 8. VLF/LF Ionospheric Reflectivity Data for 2 March 1979 (DAY 061) Solar Particle Event (contd)

3 April 1979 Solar Proton Event

DAY	093
Report Figure:	9
Related Solar Flare:	No flare identified
Start of Ionospheric Disturbance:	0600 UT
Time of Maximum 13-25 MeV Proton Flux:	5 April 0400 UT
Maximum Flux:	0.2 particles/cm^2 sec sr MeV
Length of Particle Event:	4 days
Lowest 16 kHz Reflection Height:	61 km
30 MHz Riometer Absorption:	2 dB
Solar Zenith Angle Range:	71° - 99°
Illumination Conditions:	Day-night

During the period from 27 March (DAY 086) through 8 April (DAY 098) two energetic particle disturbances occurred. The first was a low energy event. As seen in parts T and U, the 1 MeV protons reached a maximum of about 800 particles/cm^2 sec sr MeV while the 20 MeV protons remained less than 2×10^{-3}. Although the 1 MeV flux stayed above 1/cm^2 sec sr MeV from 27 March through 3 April the ionosounding parameters only showed disturbance effects on 28 March (DAY 087) when the particle flux was above 100 particles/cm^2 sec sr MeV.

On 3 April (DAY 093) a second disturbance occurred. This event had high energy protons and lasted about 4 days.

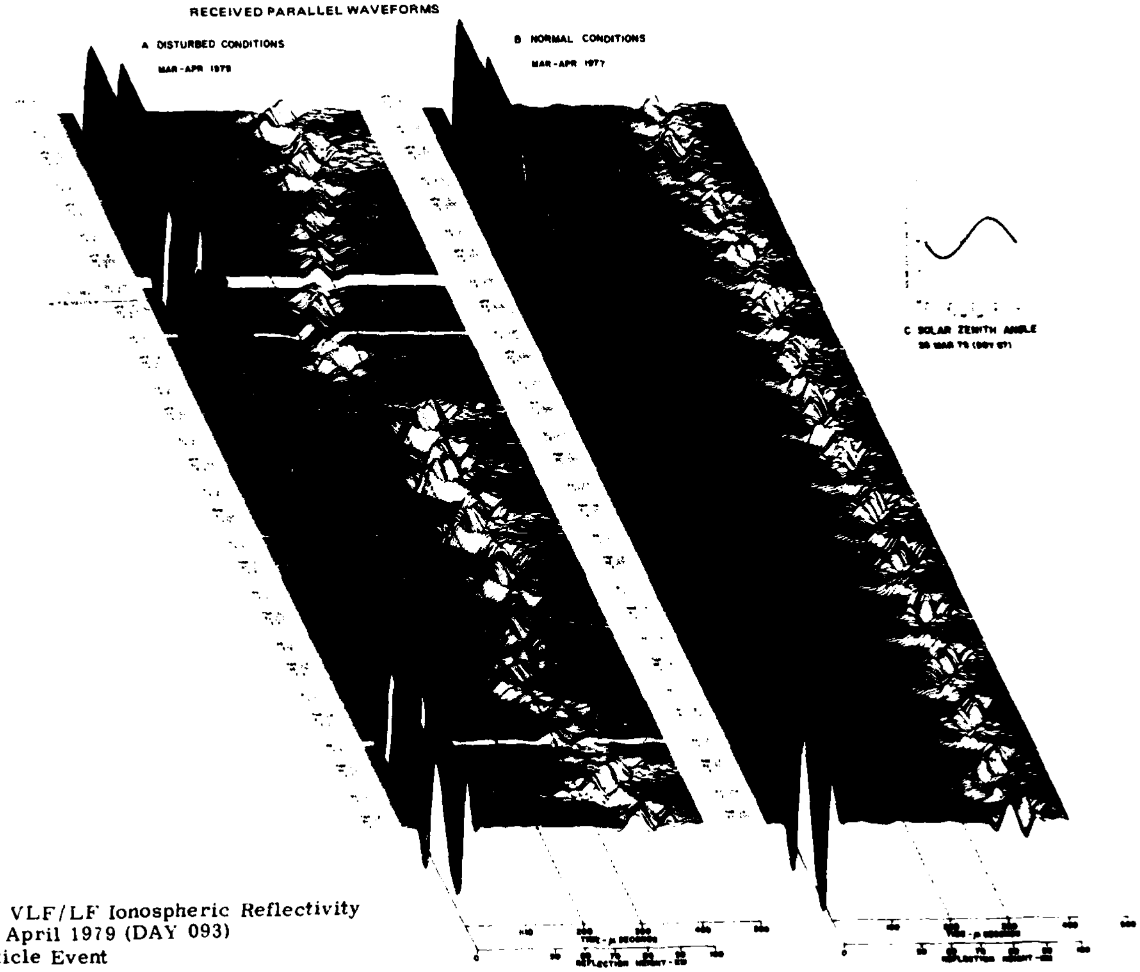


Figure 9. VLF/LF Ionospheric Reflectivity Data for 3 April 1979 (DAY 093) Solar Particle Event

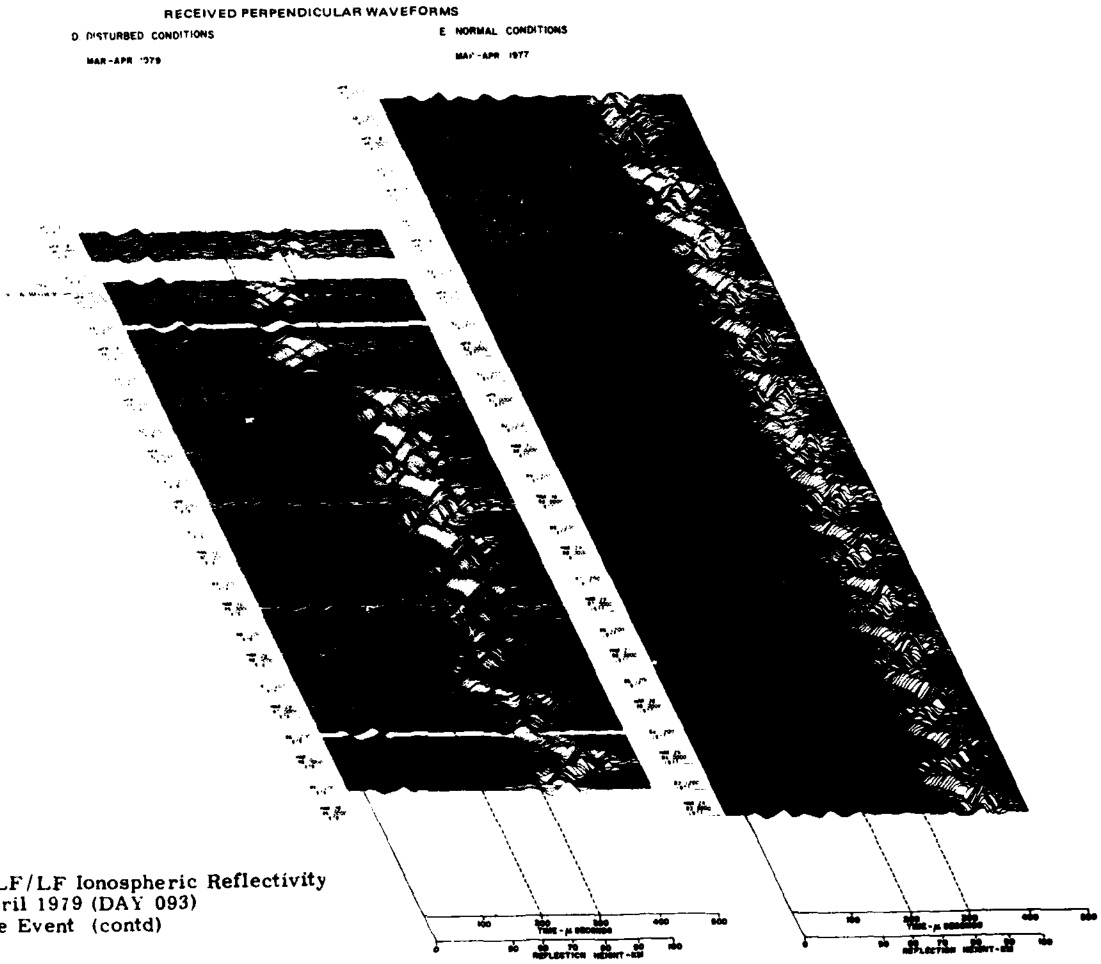


Figure 9. VLF/LF Ionospheric Reflectivity Data for 3 April 1979 (DAY 093) Solar Particle Event (contd)

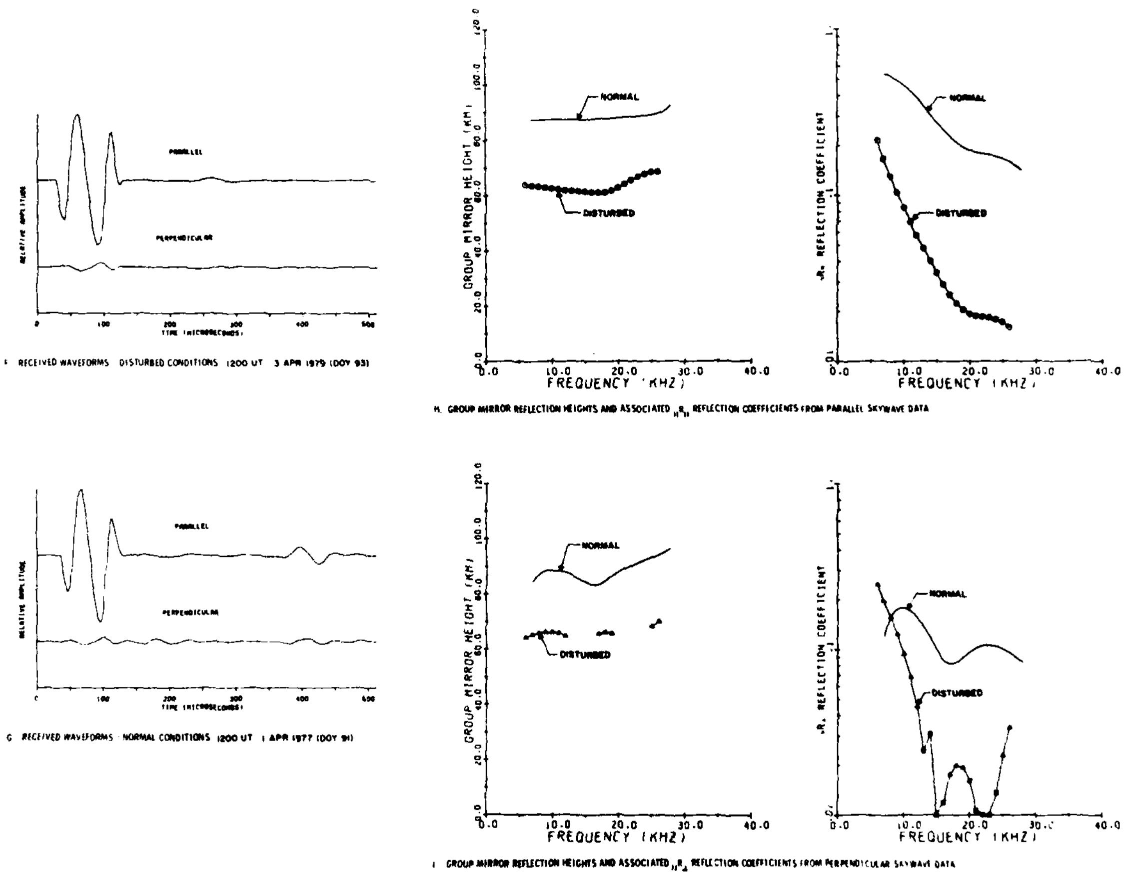
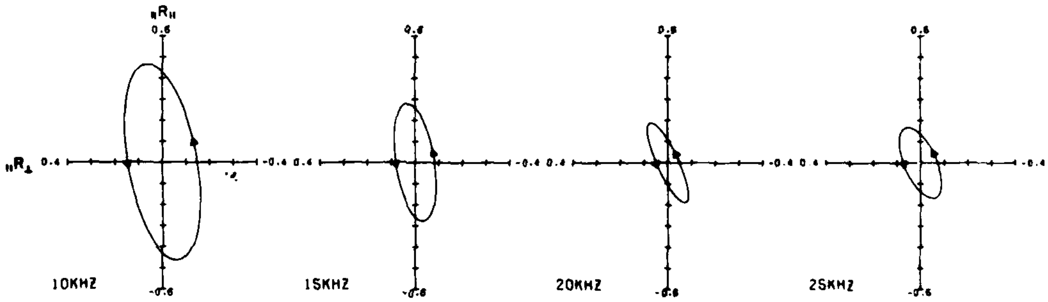


Figure 9. VLF/LF Ionospheric Reflectivity Data for 3 April 1979 (DAY 093) Solar Particle Event (contd)

J. SKYWAVE POLARIZATION ELLIPSES - DISTURBED CONDITIONS



K. SKYWAVE POLARIZATION ELLIPSES - NORMAL CONDITIONS

Figure 9. VLF/LF Ionospheric Reflectivity Data for 3 April 1979 (DAY 093) Solar Particle Event (contd)

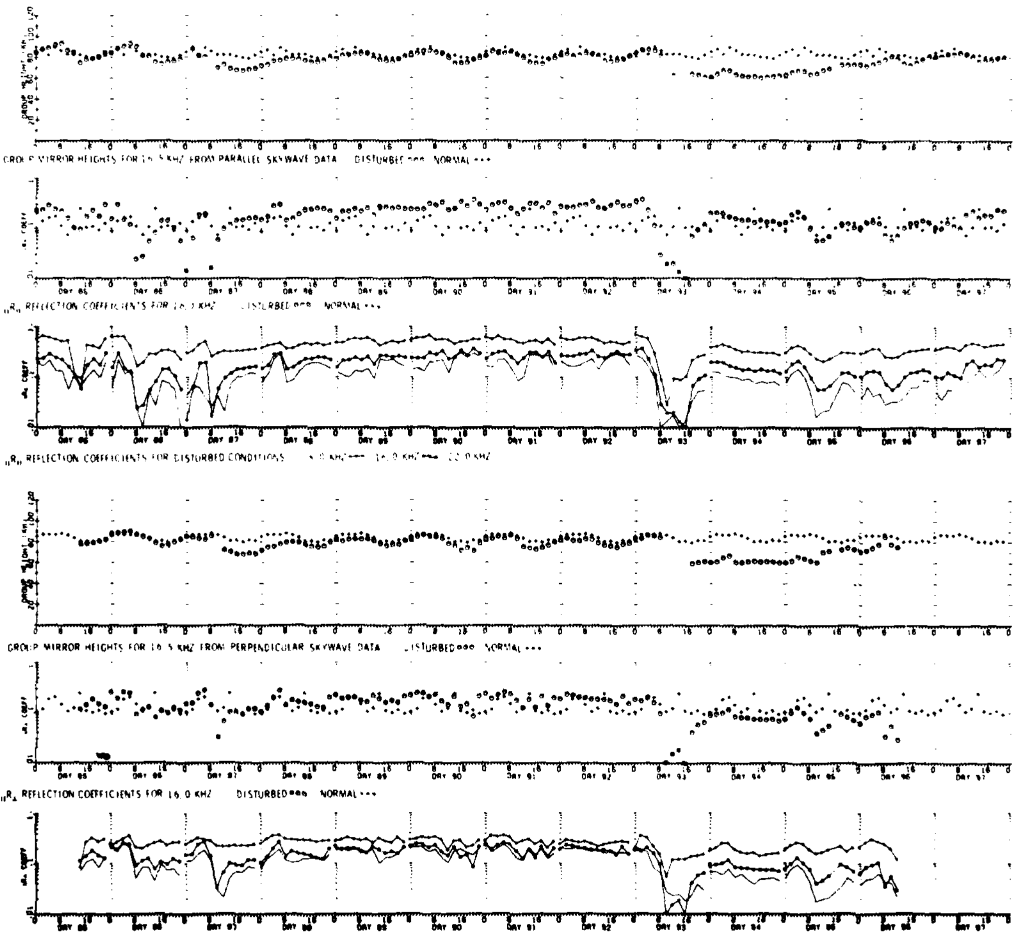


Figure 9. VLF/LF Ionospheric Reflectivity Data for 3 April 1979 (DAY 093) Solar Particle Event (contd

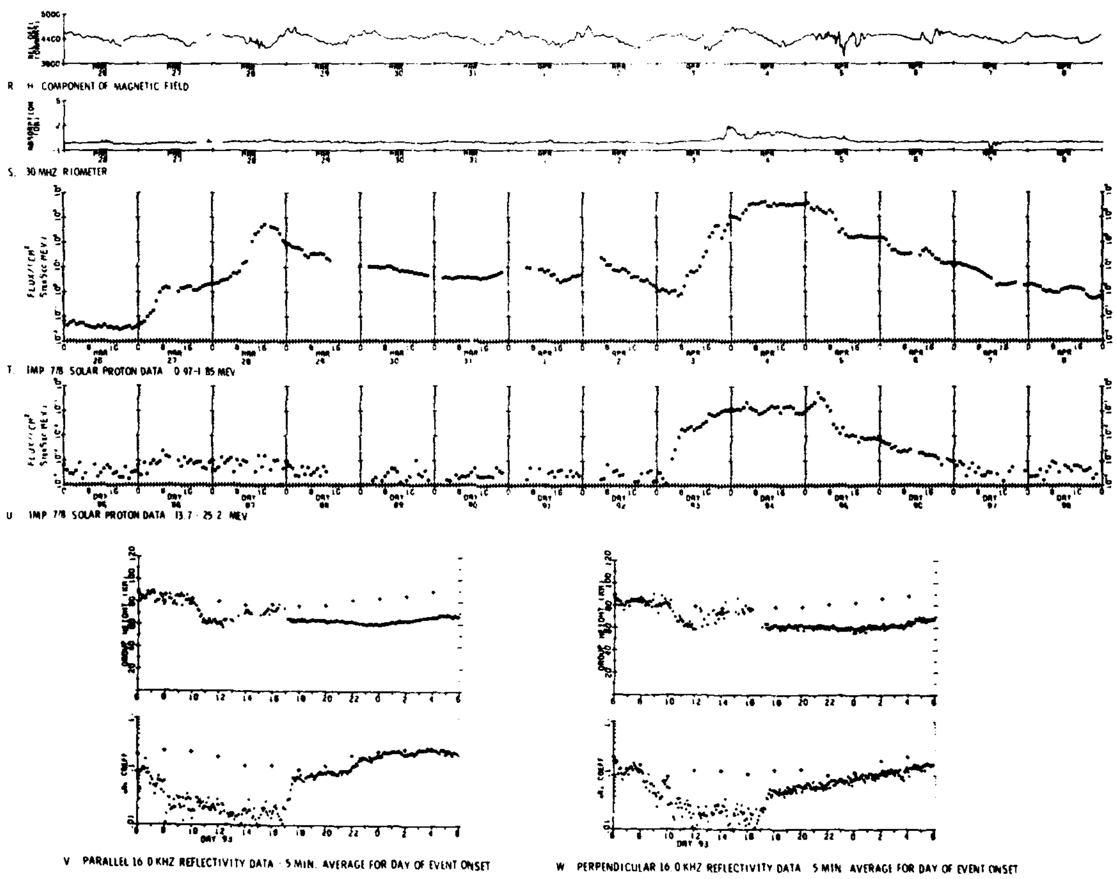


Figure 9. VLF/LF Ionospheric Reflectivity Data for 3 April 1979 (DAY 093) Solar Particle Event (contd)

6 June 1979 Solar Proton Event

DAY 157	
Report Figure 10	
Related Solar Flare:	5 June 0514 UT X-ray class: X2
Start of Ionospheric Disturbance:	6 June 1800 UT
Time of Maximum 13-25 MeV Proton Flux:	7 June 0100 UT
Maximum Flux:	20 particles/cm^2 sec sr MeV
Length of Particle Event:	6 days
Lowest 16 kHz Reflection Height:	58 km
30 MHz Riometer Absorption:	6 dB
Solar Zenith Angle Range:	54° - 82°
Illumination Conditions:	Daytime

This strong energetic particle event is typical of events occurring during continuous solar illumination conditions. Both reflection heights curves (parts L and O) showed a drop in the $\parallel$ and $\perp$ heights to about 58 km. This was followed by a gradual return to normal diurnal conditions over about 7 days. The diurnal height variation seen before and after the event is not seen during the event and recovery. The parallel reflection coefficients (part N) show a brief drop at event onset and then an increase; the coefficients were stronger on 7 June (DAY 158) than before the event onset. This increase was followed by a gradual decrease to normal levels. The perpendicular reflection coefficient (part Q) did not show the increase seen in the parallel data. During the disturbance, the waves were reflecting from lower altitudes where higher densities inhibit conversion of the parallel to the perpendicular component.

The strong spike seen in the 30 MHz data (part S) on 6 June (DAY 157) is due to a strong solar flare which occurred subsequent to the particle event onset.

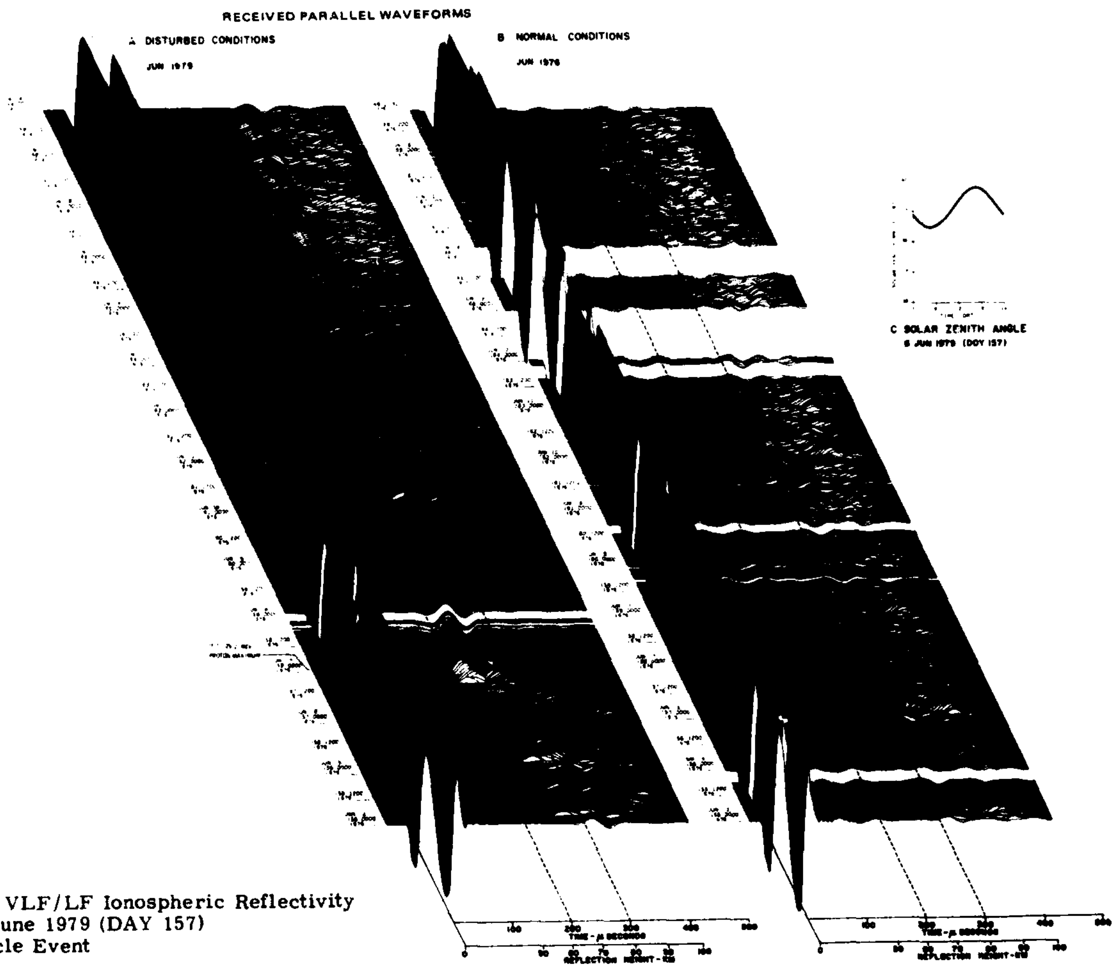


Figure 10. VLF/LF Ionospheric Reflectivity Data for 6 June 1979 (DAY 157) Solar Particle Event

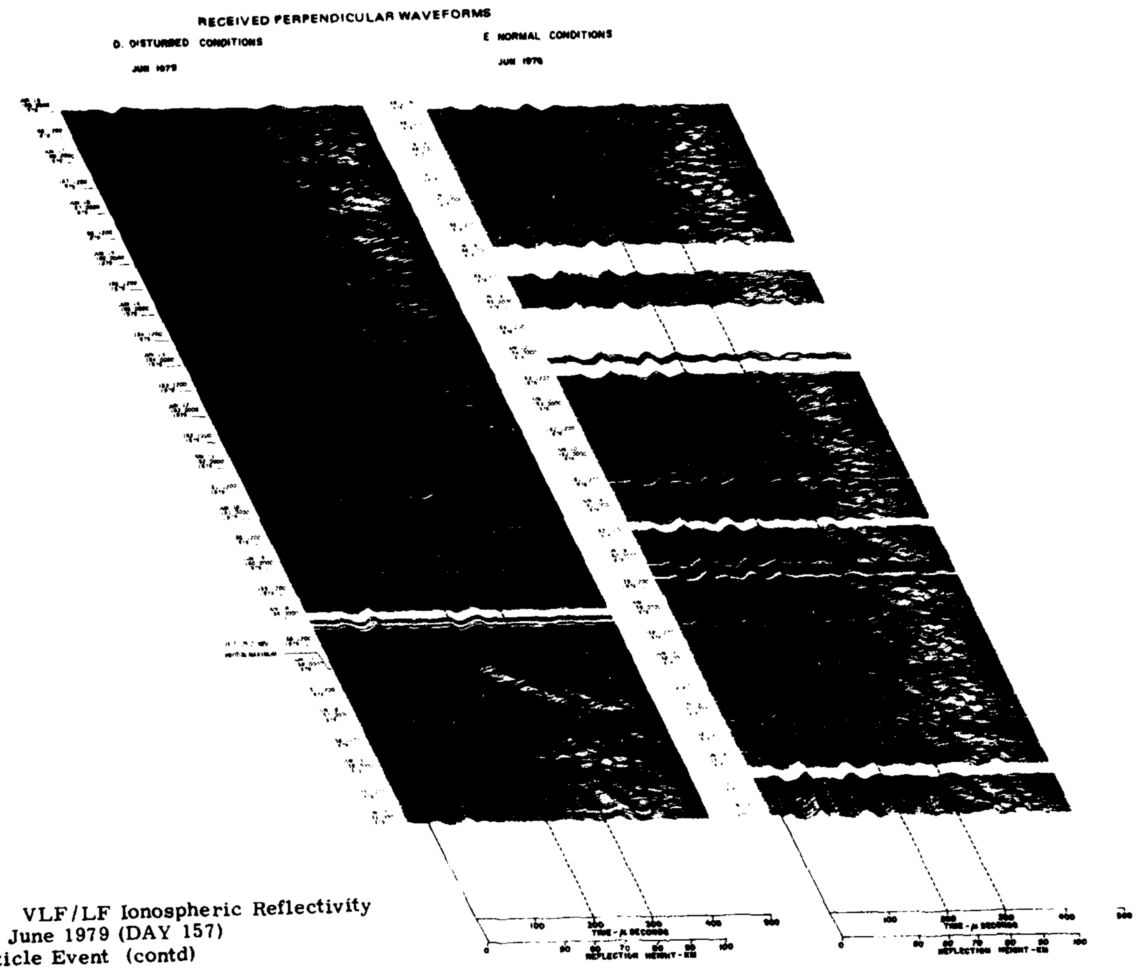
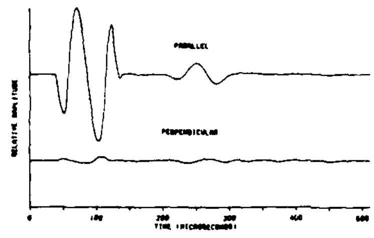
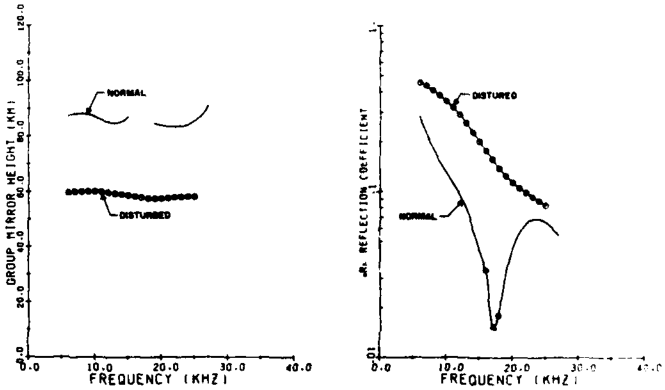


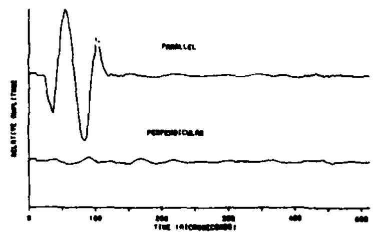
Figure 10. VLF/LF Ionospheric Reflectivity
Data for 6 June 1979 (DAY 157)
Solar Particle Event (contd)



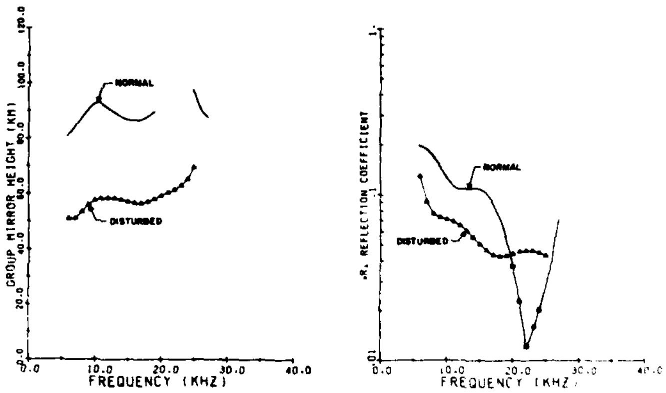
F. RECEIVED WAVEFORMS - DISTURBED CONDITIONS 0200 UT 7 JUN 1979 (DOY 158)



H. GROUP MIRROR REFLECTION HEIGHTS AND ASSOCIATED $_{\parallel}R_{\parallel}$ REFLECTION COEFFICIENTS FROM PARALLEL SKYWAVE DATA

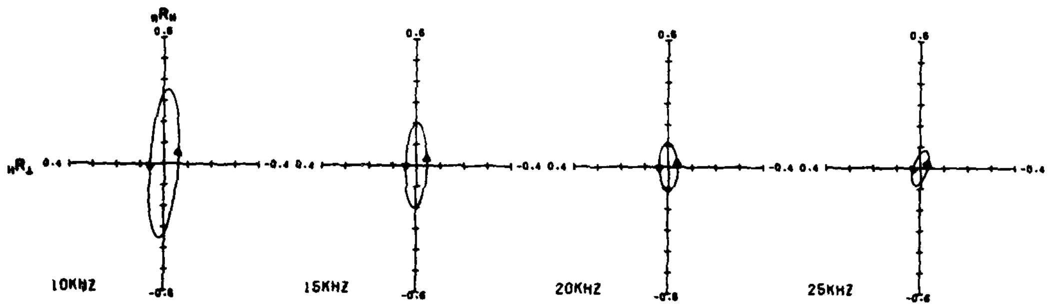


G. RECEIVED WAVEFORMS - NORMAL CONDITIONS 0800 UT 6 JUN 1979 (DOY 157)

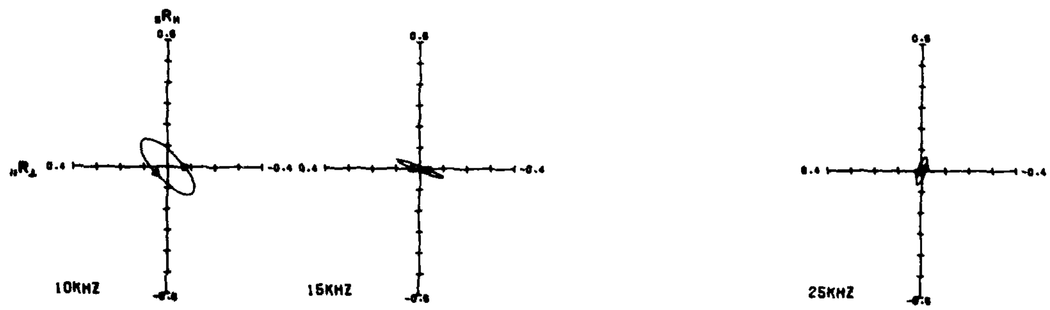


I. GROUP MIRROR REFLECTION HEIGHTS AND ASSOCIATED $_{\parallel}R_{\perp}$ REFLECTION COEFFICIENTS FROM PERPENDICULAR SKYWAVE DATA

Figure 10. VLF/LF Ionospheric Reflectivity Data for 6 June 1979 (DAY 157) Solar Particle Event (contd)



J. SKYWAVE POLARIZATION ELLIPSES - DISTURBED CONDITIONS



K. SKYWAVE POLARIZATION ELLIPSES - NORMAL CONDITIONS

Figure 10. VLF/LF Ionospheric Reflectivity Data for 6 June 1979 (DAY 157) Solar Particle Event (contd)

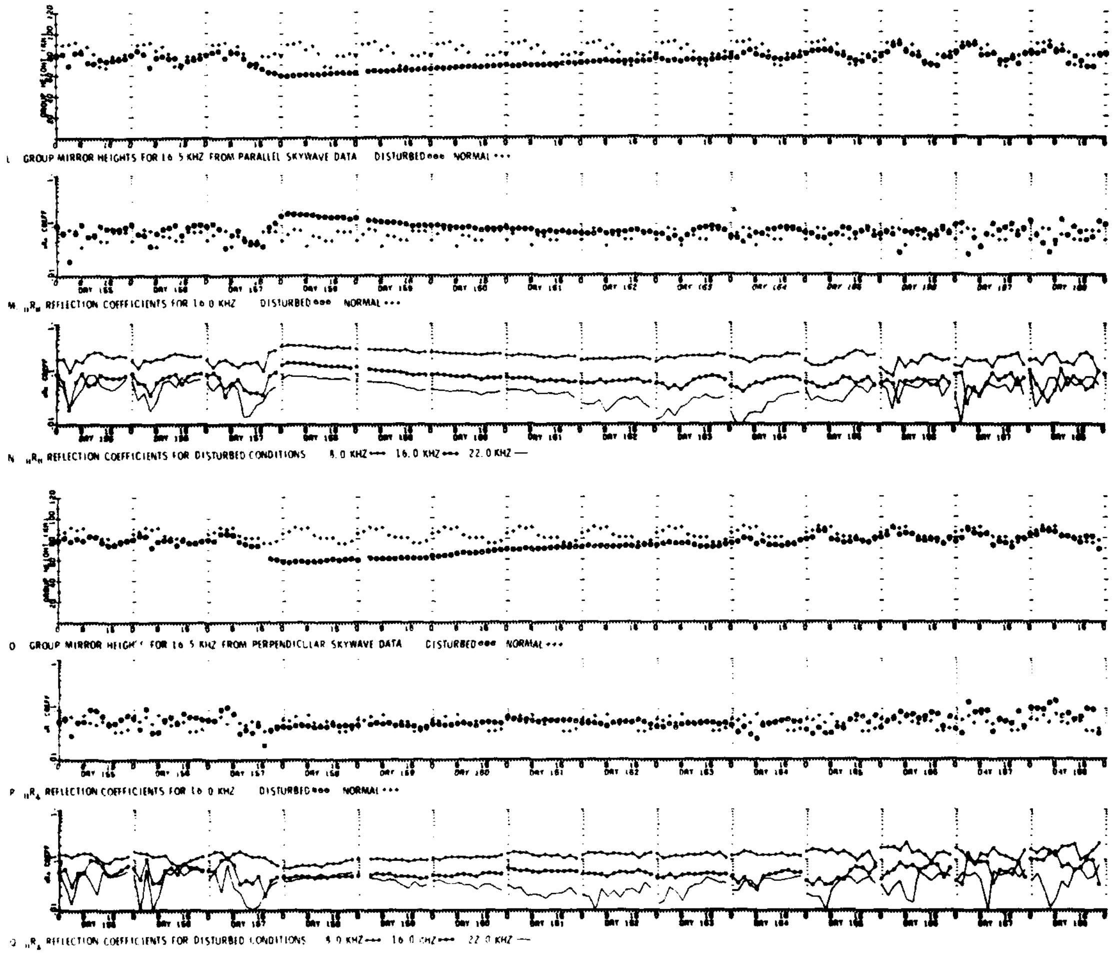


Figure 10. VLF/LF Ionospheric Reflectivity Data for 6 June 1979 (DAY 157) Solar Particle Event (contd)

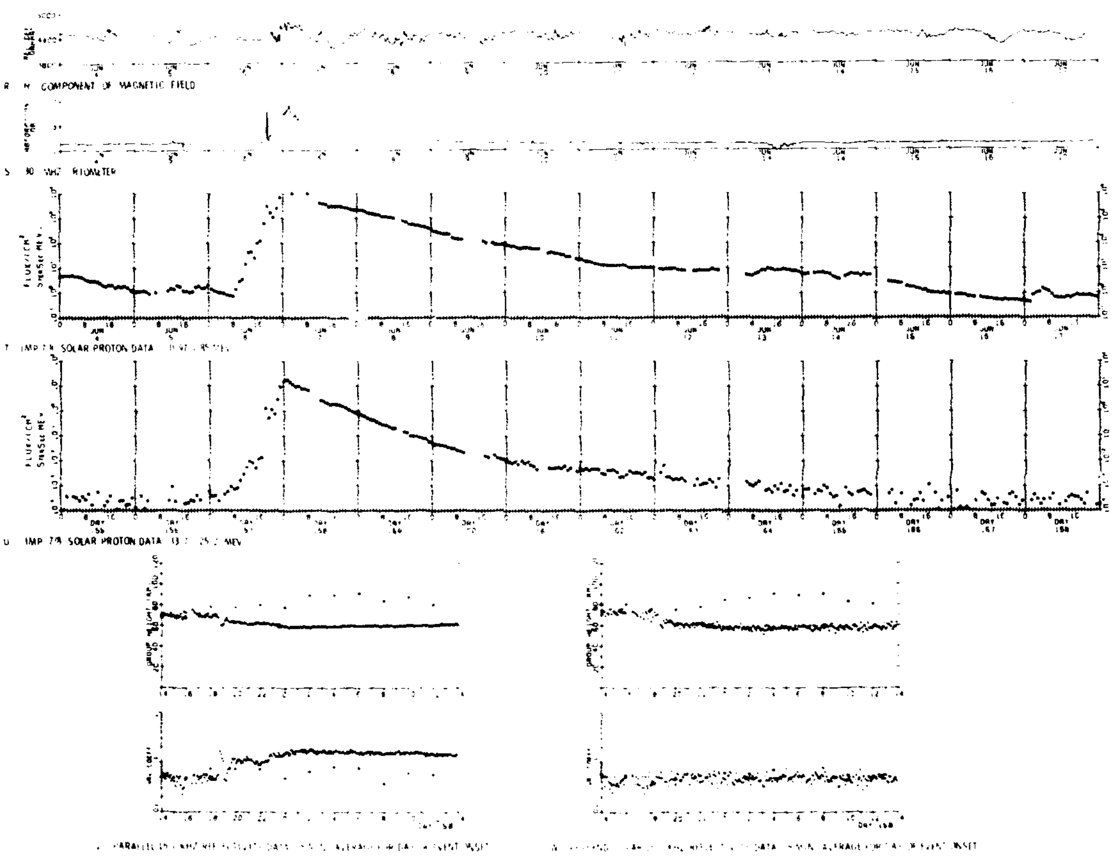


Figure 10. VLF/LF Ionospheric Reflectivity Data for 6 June 1979 (DAY 157) Solar Particle Event (contd)

1 August 1979 Solar Proton Event

DAY 213	
Report Figure: 11	
Related Solar Flare:	N/A
Start of Ionospheric Disturbance:	2000 UT
Time of Maximum 13-25 MeV Proton Flux:	7 August 0600 UT
Maximum Flux:	0.035 particles/cm^2 sec sr MeV
Length of Particle Event:	18 days
Lowest 16 kHz Reflection Height:	68 km
30 MHz Riometer Absorption:	< 0.5 dB
Solar Zenith Angle Range:	60° - 88°
Illumination Conditions:	Daytime

This event was a rather persistent low level disturbance. The parallel reflection heights remained depressed at about 70 km from 1 August (DAY 213) through 19 August (DAY 231) when the effects of another event are seen (Figure 12). As is typical of most daytime disturbances the effects on the reflection coefficients increased with frequency, being greater at 22 kHz than at 8 kHz.

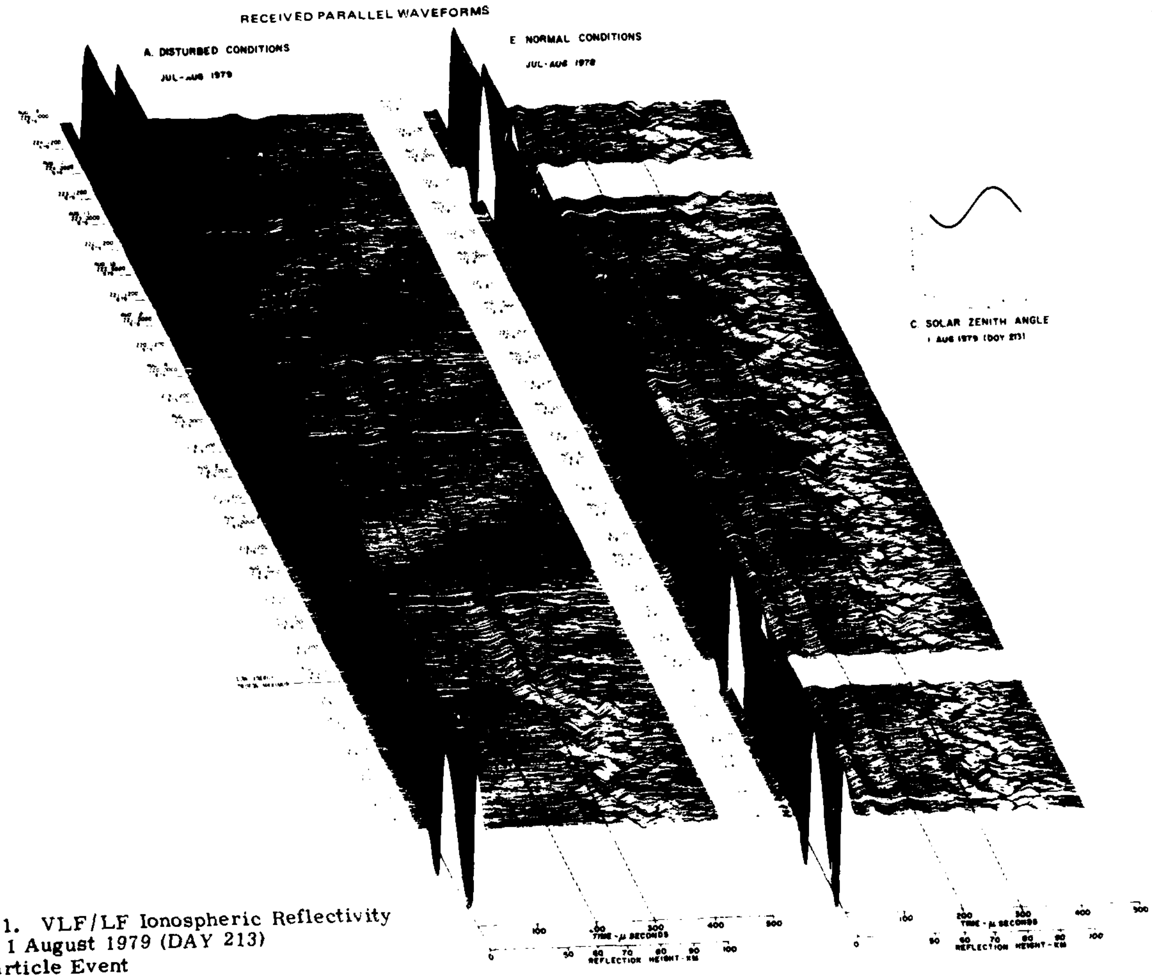


Figure 11. VLF/LF Ionospheric Reflectivity Data for 1 August 1979 (DAY 213) Solar Particle Event

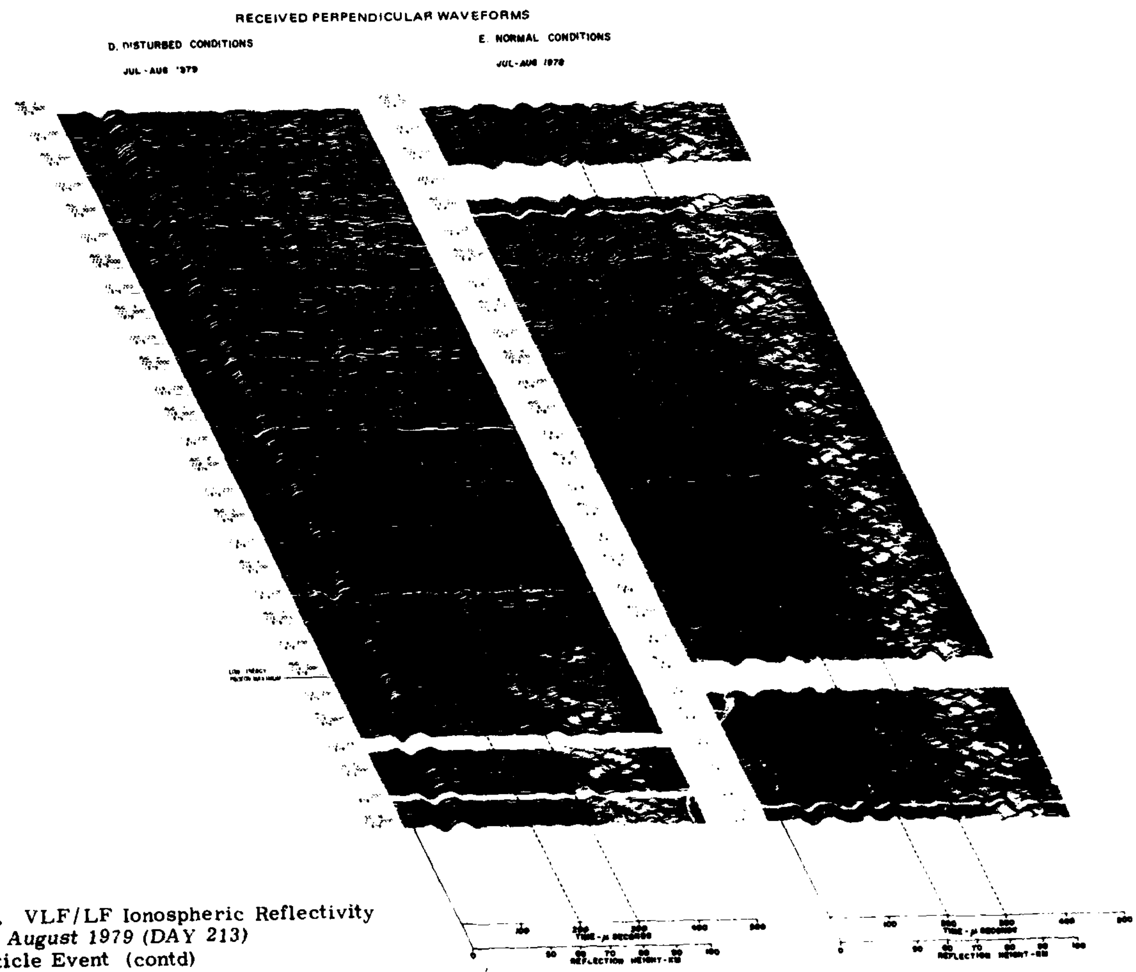


Figure 11. VLF/LF Ionospheric Reflectivity Data for 1 August 1979 (DAY 213) Solar Particle Event (contd)

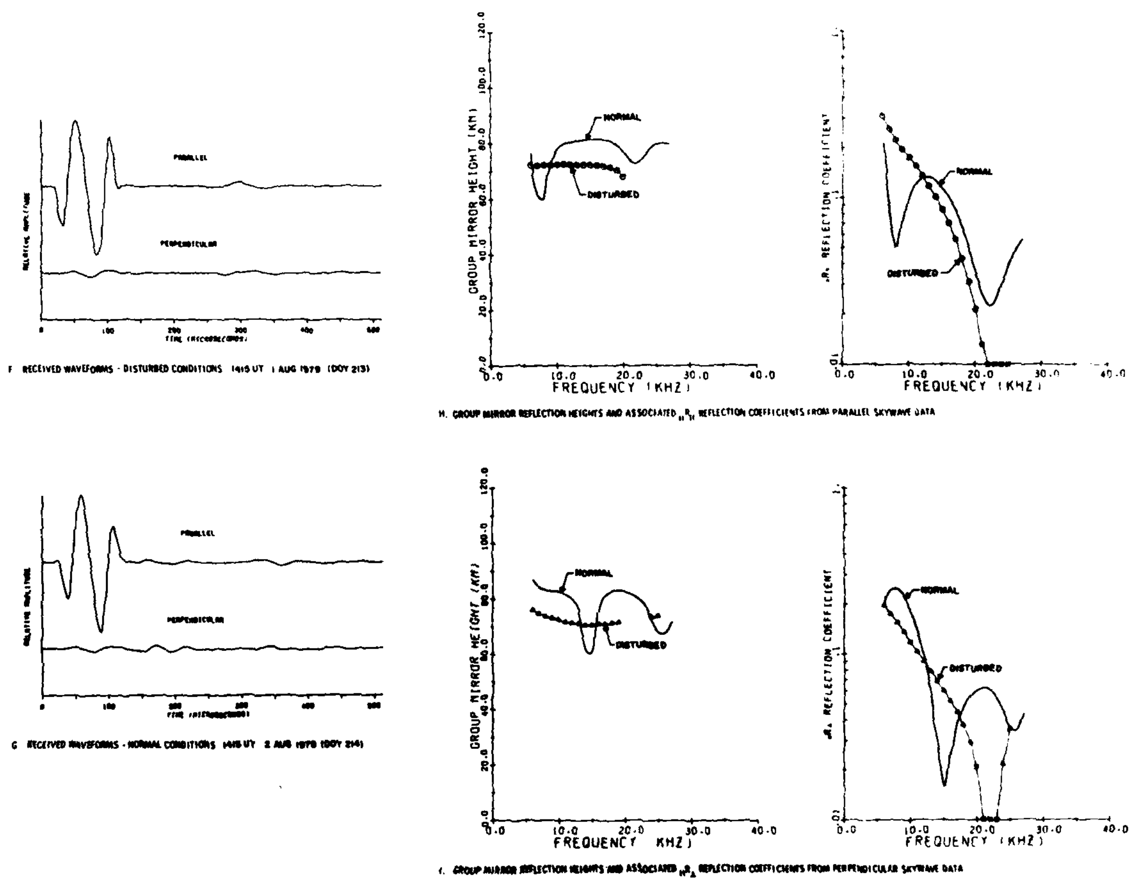
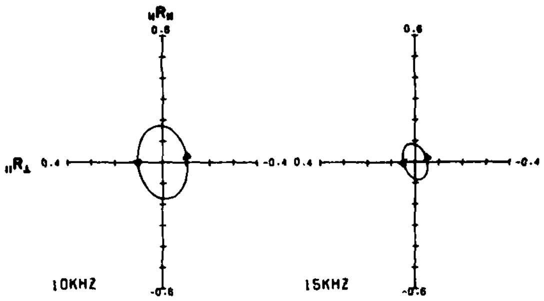
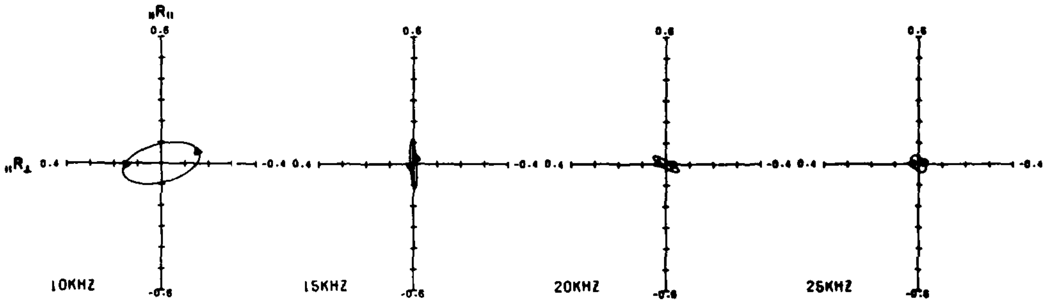


Figure 11. VLF/LF Ionospheric Reflectivity Data for 1 August 1979 (DAY 213) Solar Particle Event (contd)



J. SKYWAVE POLARIZATION ELLIPSES - DISTURBED CONDITIONS



K. SKYWAVE POLARIZATION ELLIPSES - NORMAL CONDITIONS

Figure 11. VLF/LF Ionospheric Reflectivity Data for 1 August 1979 (DAY 213) Solar Particle Event (contd)

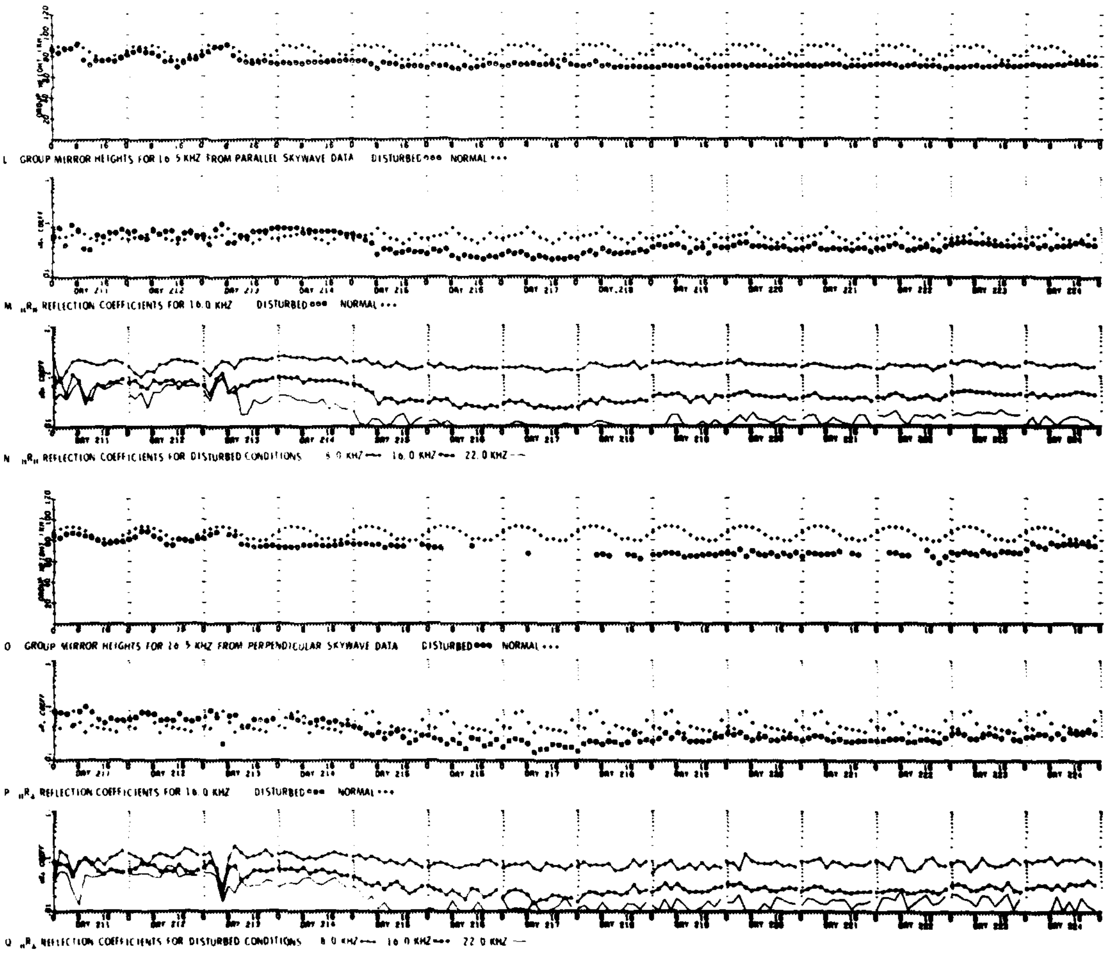


Figure 11. VLF/LF Ionospheric Reflectivity Data for 1 August 1979 (DAY 213) Solar Particle Event (contd)

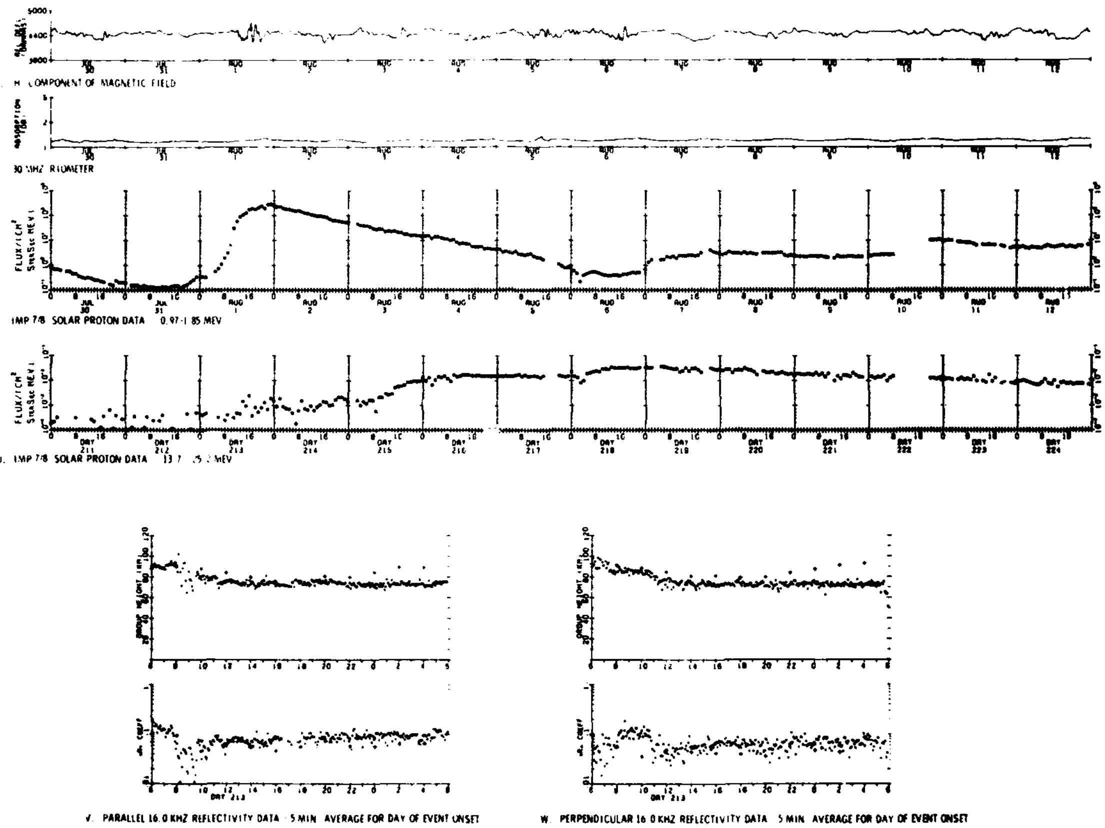


Figure 11. VLF/LF Ionospheric Reflectivity Data for 1 August 1979 (DAY 213) Solar Particle Event (contd)

19 August 1979 Solar Proton Event

DAY	231
Report Figure:	12
Related Solar Flare:	18 August 1416 UT X-ray class: x6
Start of Ionospheric Disturbance:	19 August 0100 UT
Time of Maximum 13-25 MeV Proton Flux:	20 August 0800 UT
Maximum Flux:	20 particles/cm^2 sec sr MeV
Length of Particle Event:	10 days
Lowest 16 kHz Reflection Height:	57 km
30 MHz Riometer Absorption:	4 dB
Solar Zenith Angle Range:	64° - 92°
Illumination Conditions:	Daytime

This strong event began during the recovery from a previous disturbance. Reflection heights (parts L & O) dropped from 72 km to about 57 km. Reflection heights gradually recovered over the next two weeks. The effects of the short-lived Sudden Ionospheric Disturbance (SID) resulting from an X6 flare at 1416 UT on 18 August (DAY 230) can be seen in both the parallel and perpendicular data (parts L, N, O, Q) as well as in the riometer data (part S).

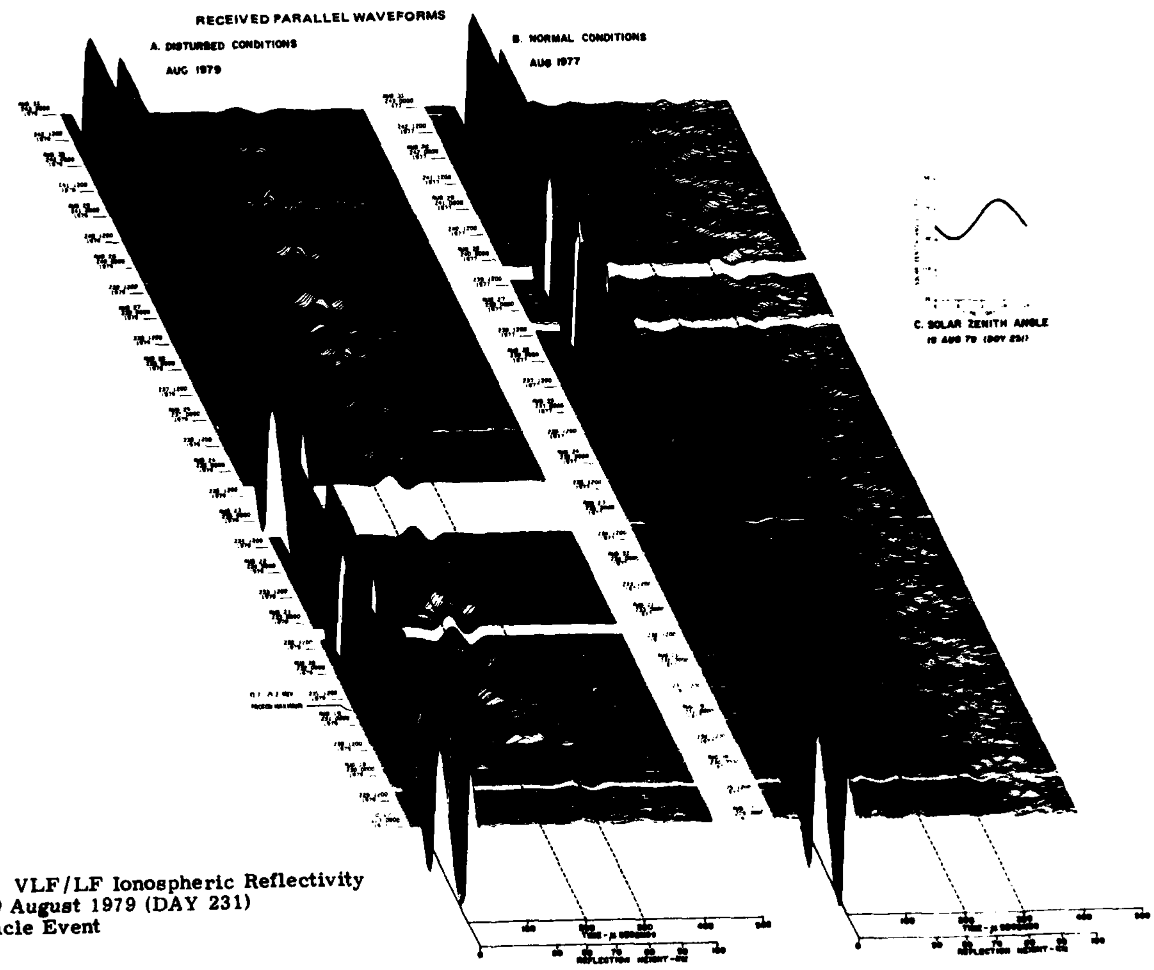


Figure 12. VLF/LF Ionospheric Reflectivity Data for 19 August 1979 (DAY 231) Solar Particle Event

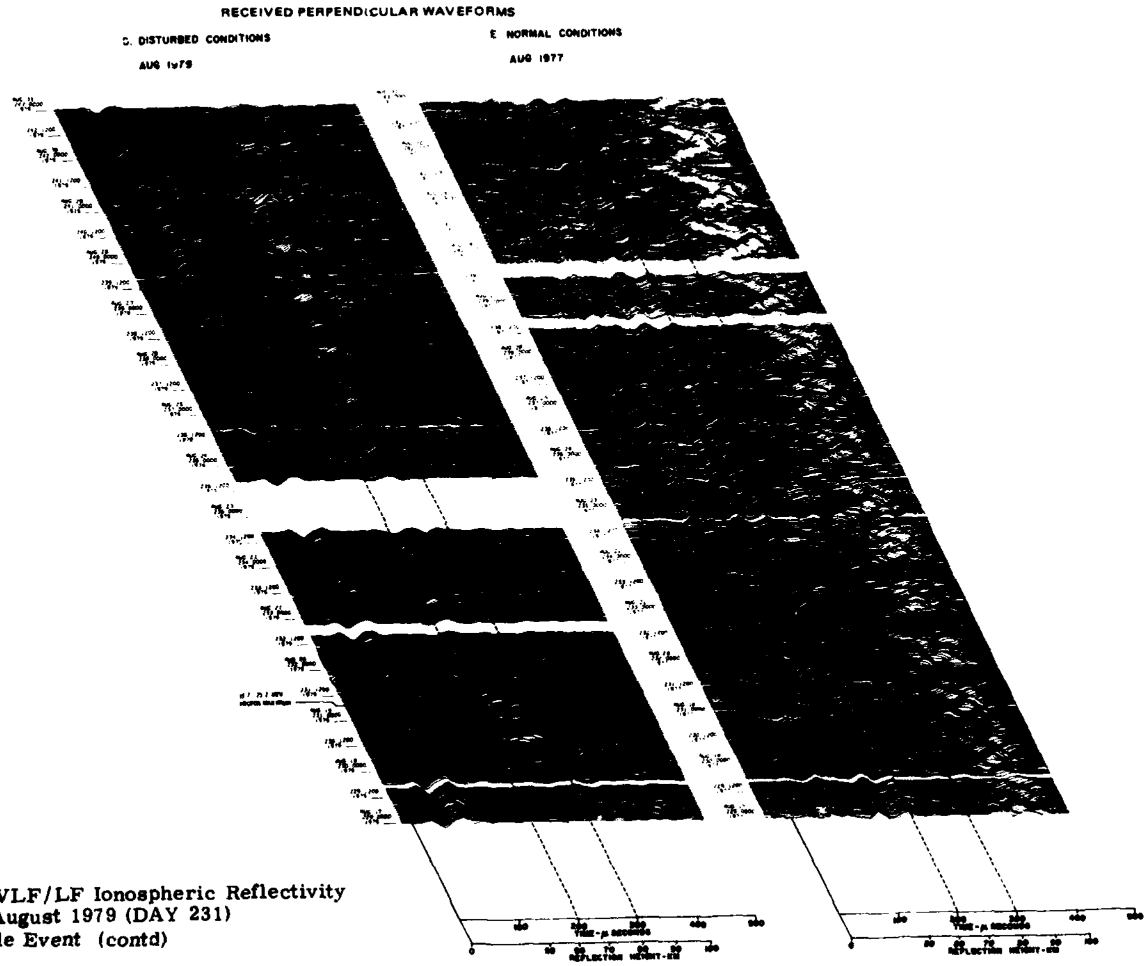


Figure 12. VLF/LF Ionospheric Reflectivity Data for 19 August 1979 (DAY 231) Solar Particle Event (contd)

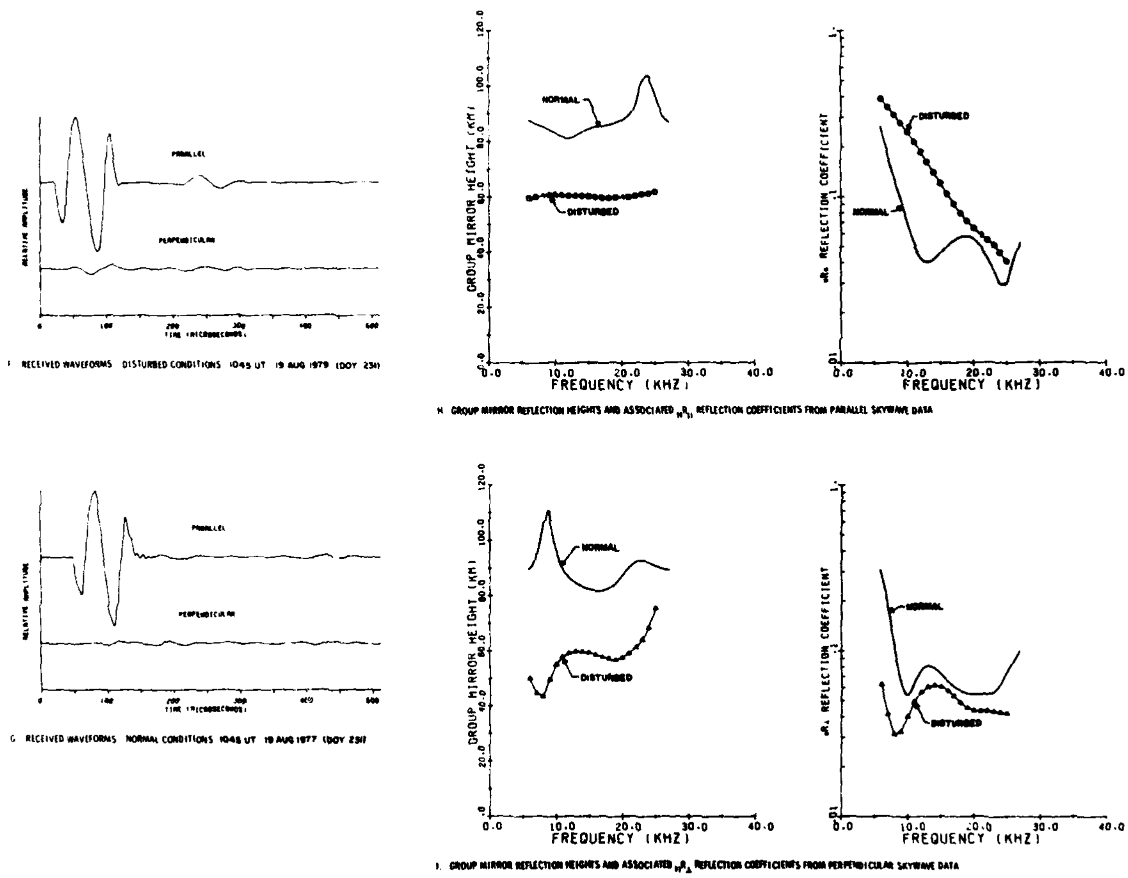
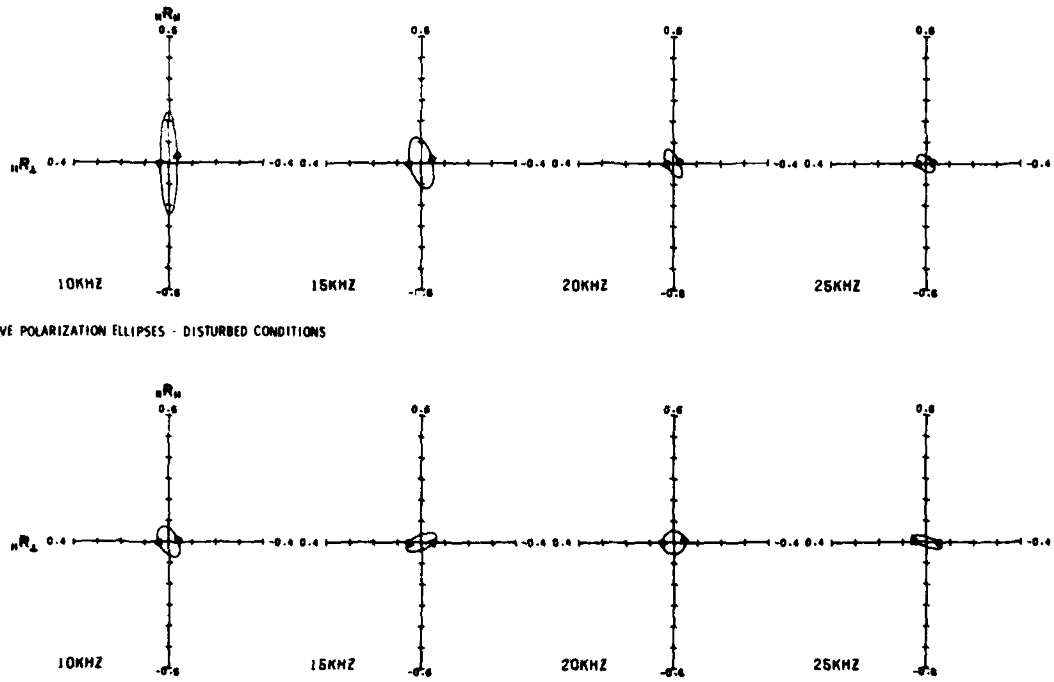


Figure 12. VLF/LF Ionospheric Reflectivity Data for 19 August 1979 (DAY 231) Solar Particle Event (contd)



J. SKYWAVE POLARIZATION ELLIPSES - DISTURBED CONDITIONS

K. SKYWAVE POLARIZATION ELLIPSES - NORMAL CONDITIONS

Figure 12. VLF/LF Ionospheric Reflectivity Data for 19 August 1979 (DAY 231) Solar Particle Event (contd)

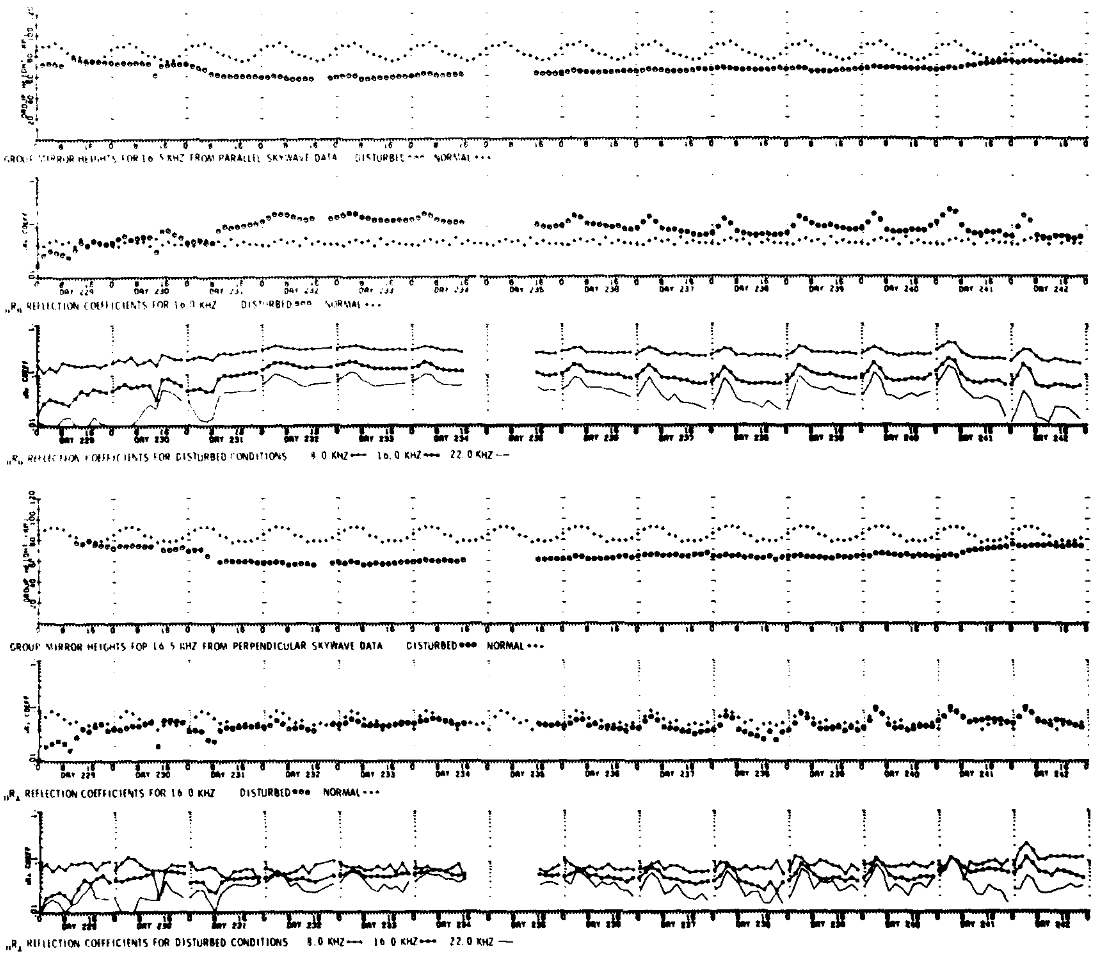


Figure 12. VLF/LF Ionospheric Reflectivity Data for 19 August 1979 (DAY 231) Solar Particle Event (contd)

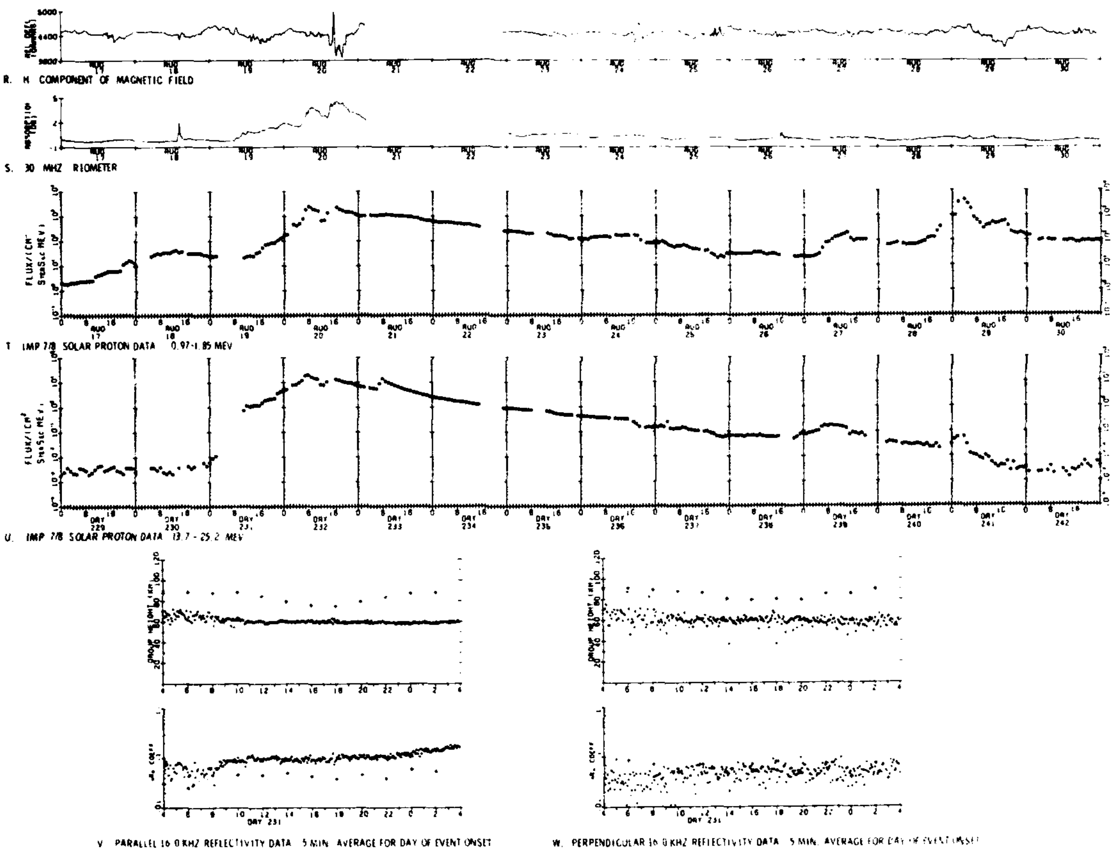


Figure 12. VLF/LF Ionospheric Reflectivity Data for 19 August 1979 (DAY 231) Solar Particle Event (contd)

8 September 1979 Solar Proton Event

DAY 251	
Report Figure: 13	
Related Solar Flare:	0652 UT X-ray class: M2
Start of Ionospheric Disturbance:	8 September 1000 UT
Time of Maximum 13-25 MeV Proton Flux:	8 September 2000 UT
Maximum Flux:	0.1 particles/cm^2 sec sr MeV
Length of Particle Event:	> 6 days
Lowest 16 kHz Reflection Height:	63 km
30 MHz Riometer Absorption:	0.5 dB
Solar Zenith Angle Range:	71° - 99°
Illumination Conditions:	Day-night

15 September 1979 Solar Proton Event

DAY 258	
Report Figure: 13	
Related Solar Flare:	14 September 0802 UT X-ray class: X2
Start of Ionospheric Disturbance:	14 September 1000 UT
Time of Maximum 13-25 MeV Proton Flux:	18 September 0000 UT
Maximum Flux:	3 particles/cm^2 sec sr MeV
Length of Particle Event:	15 days
Lowest 16 kHz Reflection Height:	58 km
30 MHz Riometer Absorption:	2 dB
Solar Zenith Angle Range:	75° - 103°
Illumination Conditions:	Day-night

The effects of two energetic particle events are seen in Figure 13. These events occurred in the day-night period at Thule AB so that a diurnal variation is seen in both the reflection heights and coefficients before and during the event. The effects of the stronger event which began on 14 September are seen primarily in the daytime reflection coefficients (part I). The lowest daytime parallel reflection height during the 14 September event was about 8 km lower than during the 8 September event. However, the nighttime reflection heights were the same for the two events. The disturbance effects from the second event lasted through the first week in October.

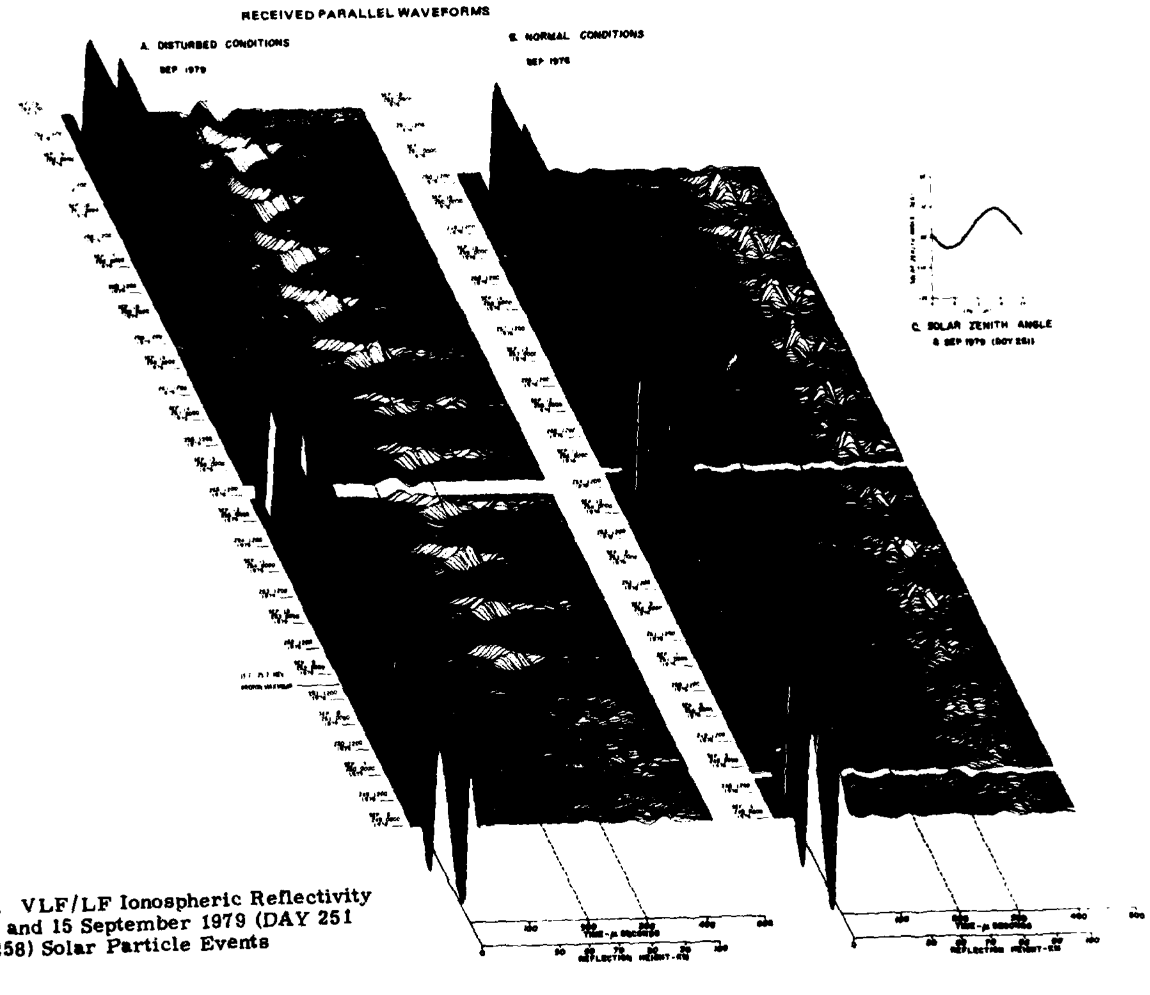


Figure 13. VLF/LF Ionospheric Reflectivity Data for 8 and 15 September 1979 (DAY 251 and DAY 258) Solar Particle Events

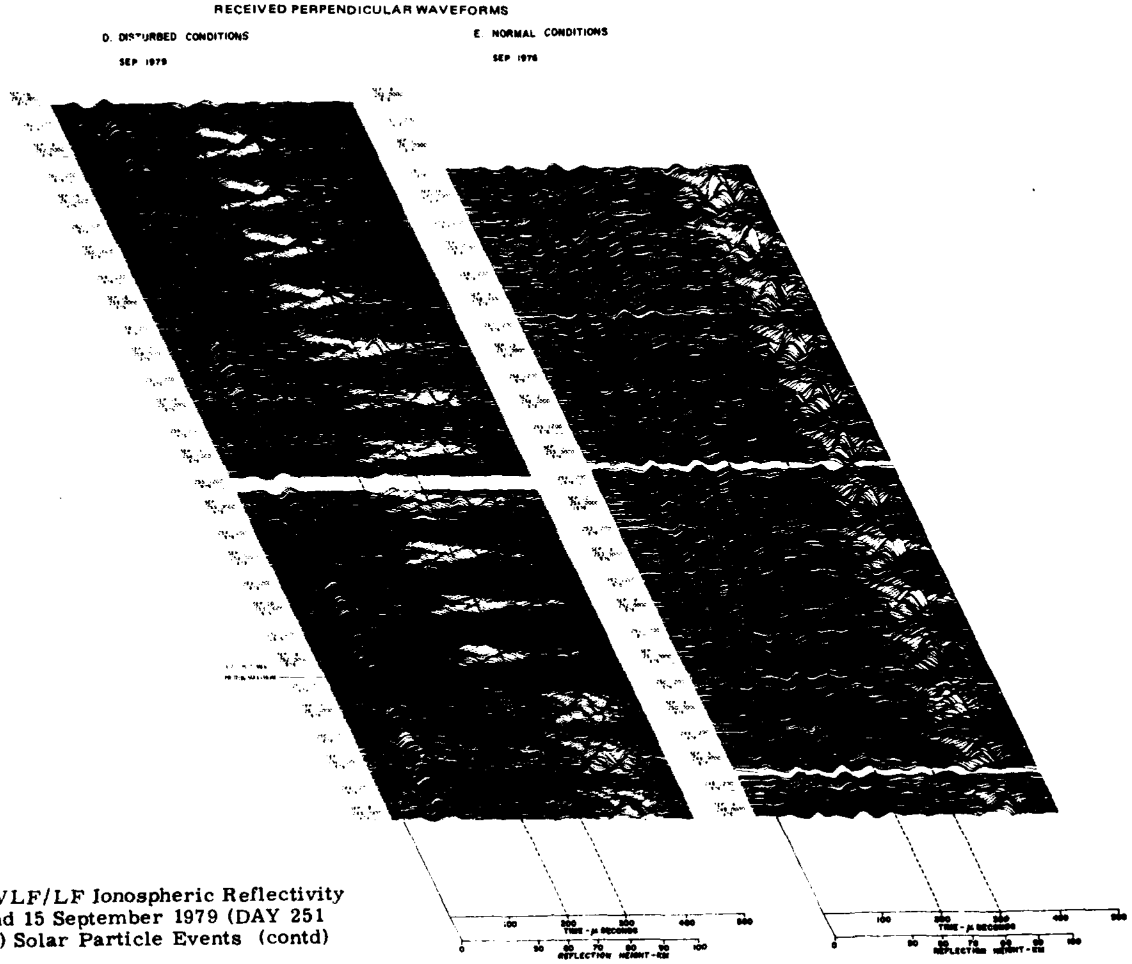


Figure 13. VLF/LF Ionospheric Reflectivity Data for 8 and 15 September 1979 (DAY 251 and DAY 258) Solar Particle Events (contd)

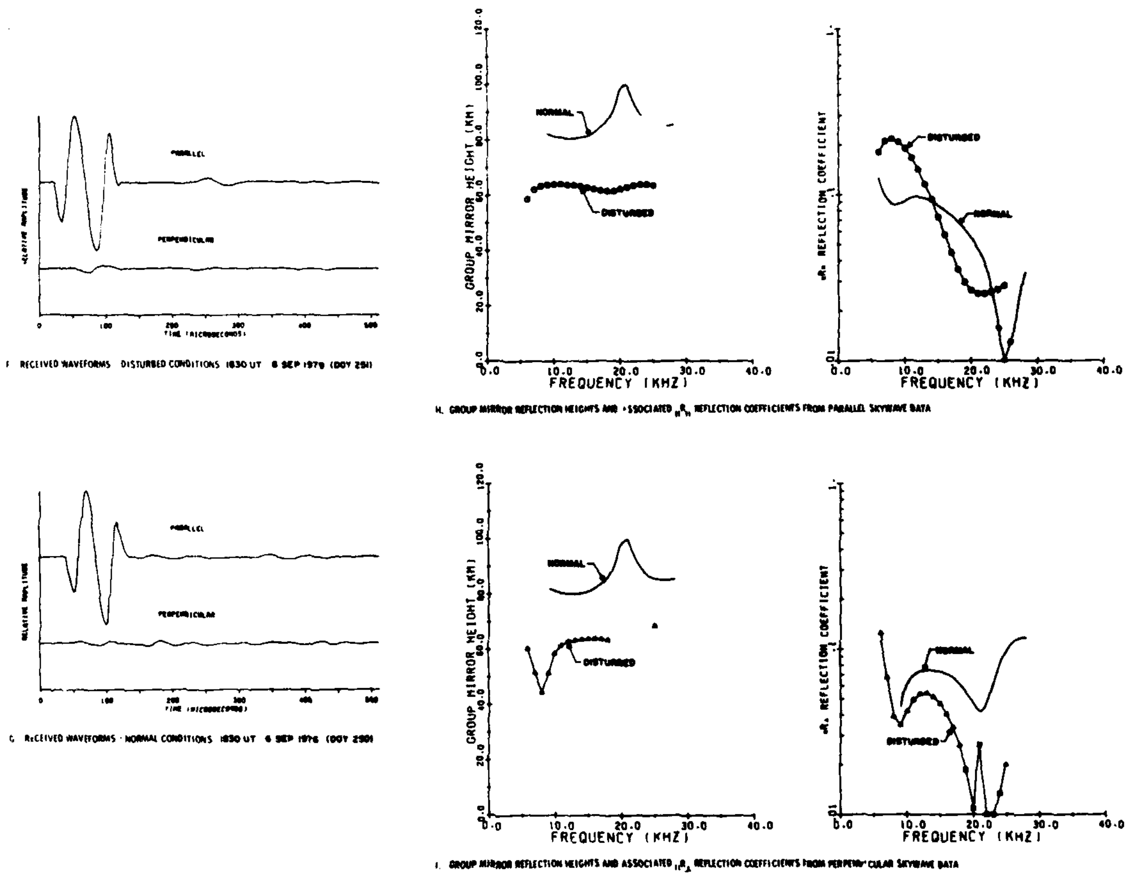
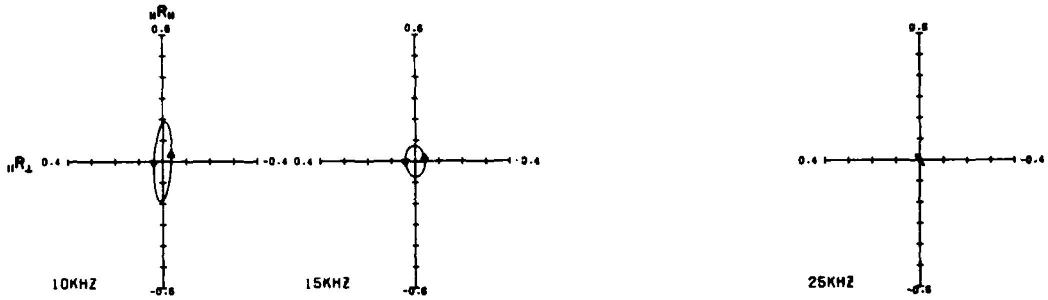
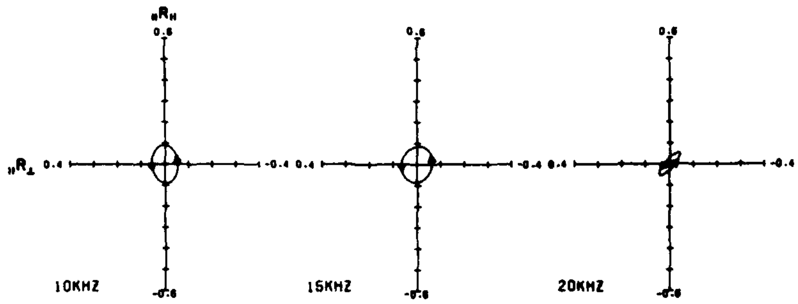


Figure 13. VLF/LF Ionospheric Reflectivity Data for 8 and 15 September 1979 (DAY 251 and DAY 258) Solar Particle Events (contd)



J. SKYWAVE POLARIZATION ELLIPSES - DISTURBED CONDITIONS



K. SKYWAVE POLARIZATION ELLIPSES - NORMAL CONDITIONS

Figure 13. VLF/LF Ionospheric Reflectivity Data for 8 and 15 September 1979 (DAY 251 and DAY 258) Solar Particle Events (contd)

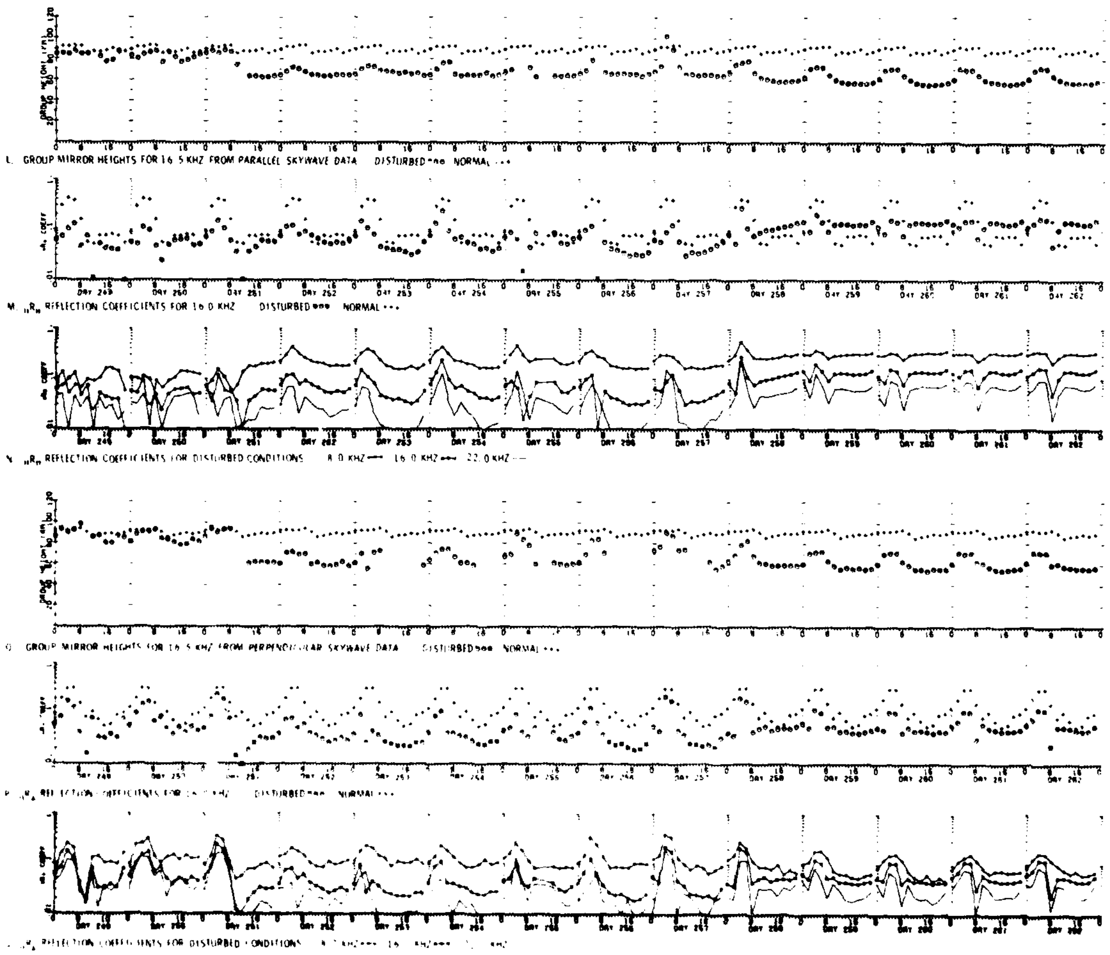


Figure 13. VLF/LF Ionospheric Reflectivity Data for 8 and 15 September 1979 (DAY 251 and DAY 258) Solar Particle Events (contd)

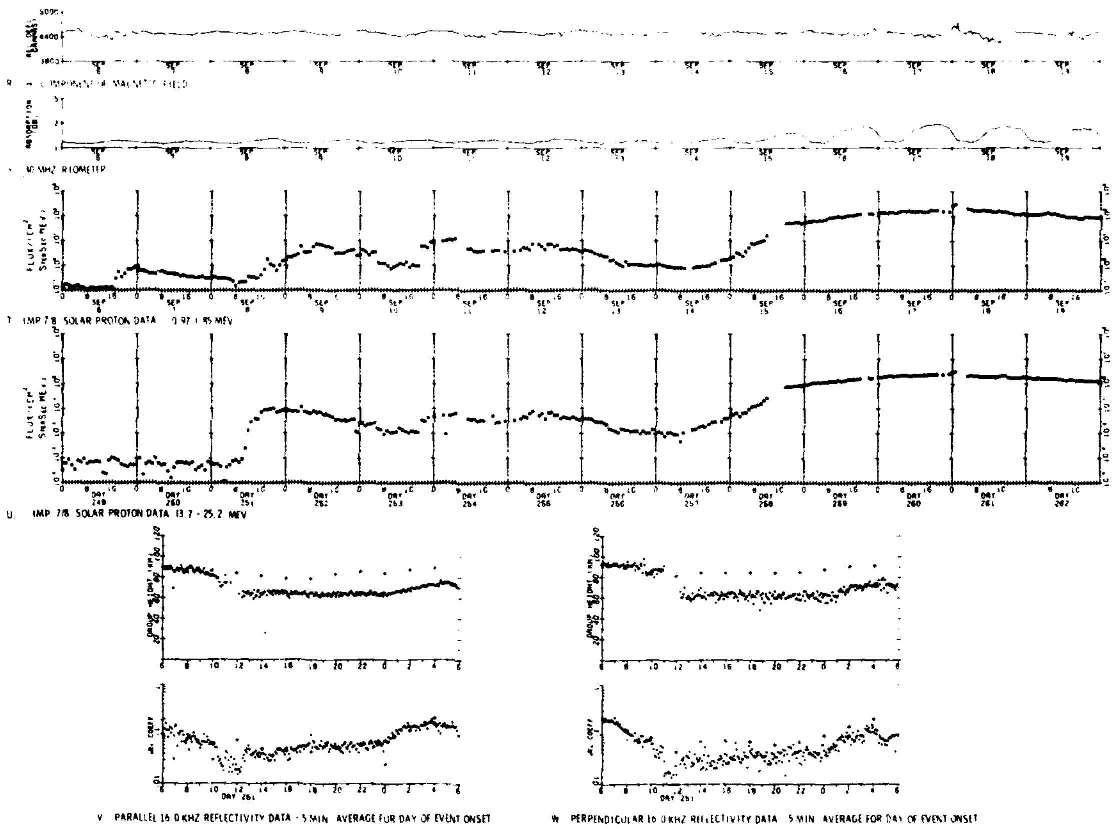


Figure 13. VLF/LF Ionospheric Reflectivity Data for 8 and 15 September 1979 (DAY 251 and DAY 258) Solar Particle Events (contd)

16 November 1979 Solar Proton Event

DAY 320	
Report Figure: 14	
Related Solar Flare:	15 November 2145 UT X-ray class: M3
Start of Ionospheric Disturbance:	16 November 0000 UT
Time of Maximum 13-25 MeV Proton Flux:	0900 UT
Maximum Flux:	3 particles/cm^2 sec sr MeV
Length of Particle Event:	5 days
Lowest 16 kHz Reflection Height:	62 km
30 MHz Riometer Absorption:	1 dB
Solar Zenith Angle Range:	95° - 123°
Illumination Conditions:	Day-night

This event occurred at the end of the day-night period. The quiet day reference curves in parts L, M, O and P show only a very small day-night change, indicating that at this time in November there is very little solar ionization below 90 km. During the event a small diurnal variation is seen in parts L and O. It is probable that at noontime there was enough residual solar illumination below 90 km for photodetachment of electrons from negative ions; but no photoionization. This detachment would have caused enhanced electron densities resulting in the lower reflection height and the small diurnal variation seen on the first three days of the event.

On 21 November (DAY 325) the effects of a small secondary particle event are seen during the recovery from the first event. The reflection parameters had returned to normal by 24 November (DAY 328).

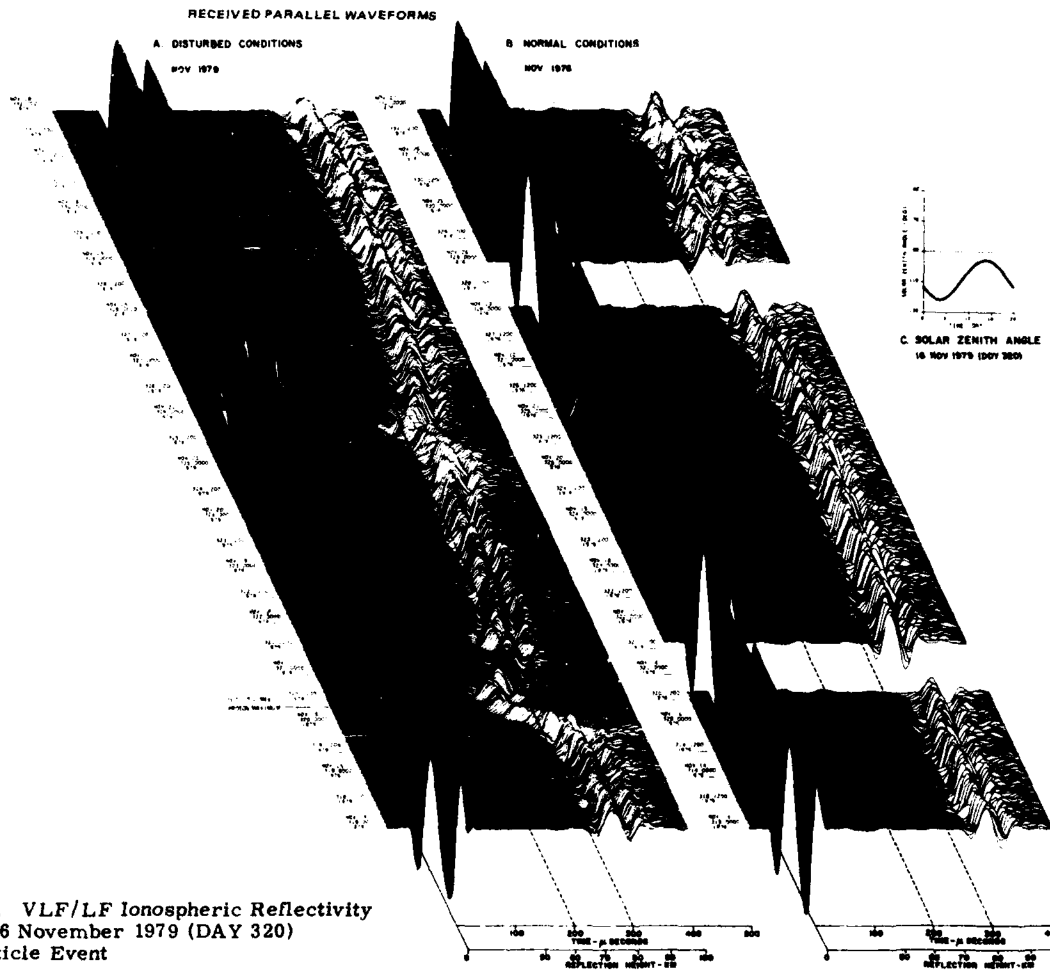


Figure 14. VLF/LF Ionospheric Reflectivity Data for 16 November 1979 (DAY 320) Solar Particle Event

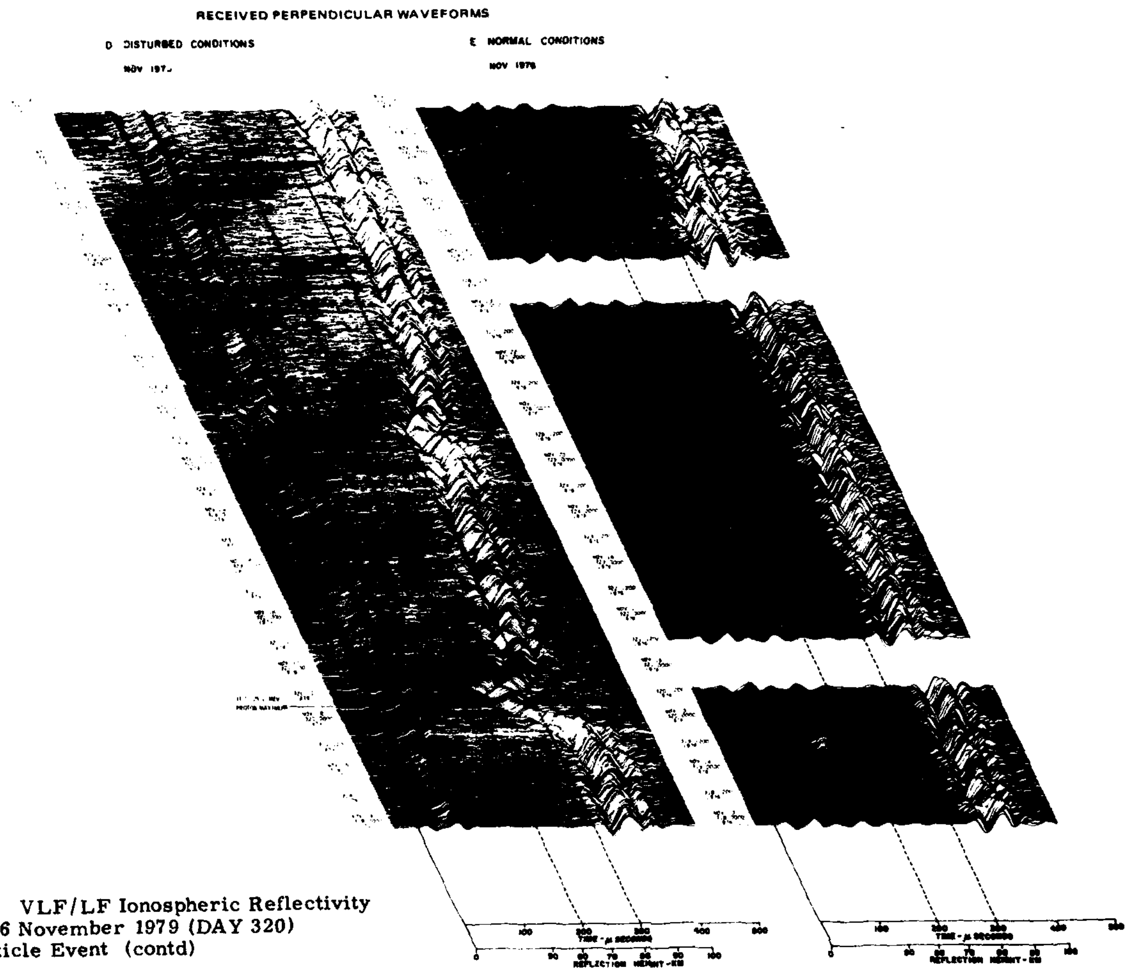


Figure 14. VLF/LF Ionospheric Reflectivity Data for 16 November 1979 (DAY 320) Solar Particle Event (contd)

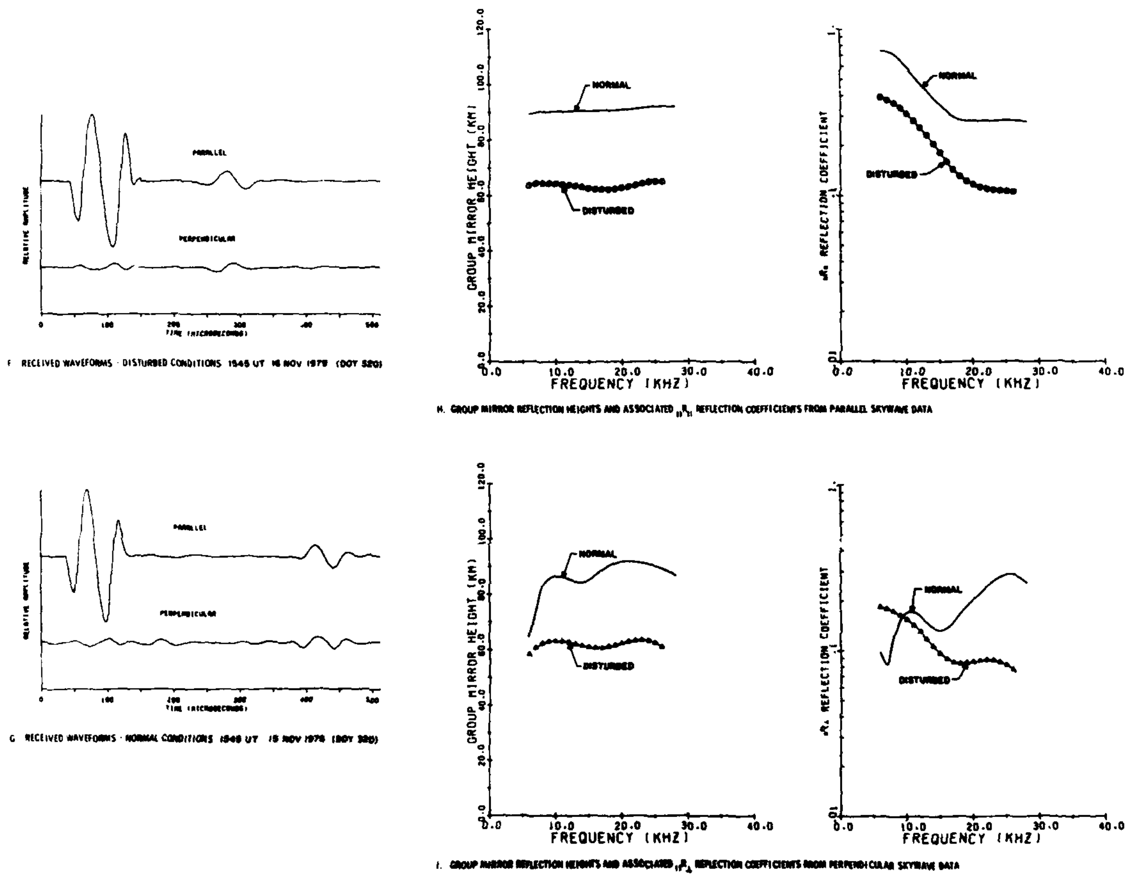
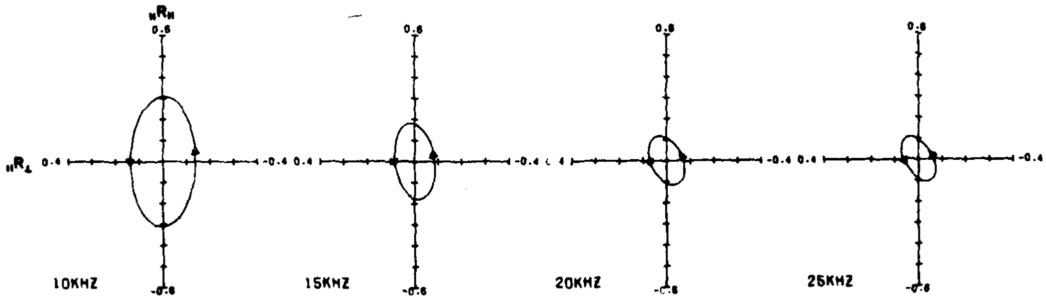
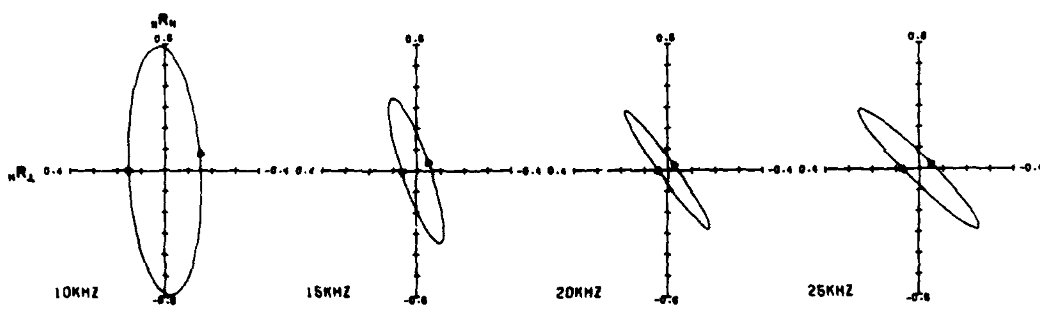


Figure 14. VLF/LF Ionospheric Reflectivity Data for 16 November 1979 (DAY 320) Solar Particle Event (contd)



J. SKYWAVE POLARIZATION ELLIPSES - DISTURBED CONDITIONS



K. SKYWAVE POLARIZATION ELLIPSES - NORMAL CONDITIONS

Figure 14. VLF/LF Ionospheric Reflectivity Data for 16 November 1979 (DAY 320) Solar Particle Event (contd)

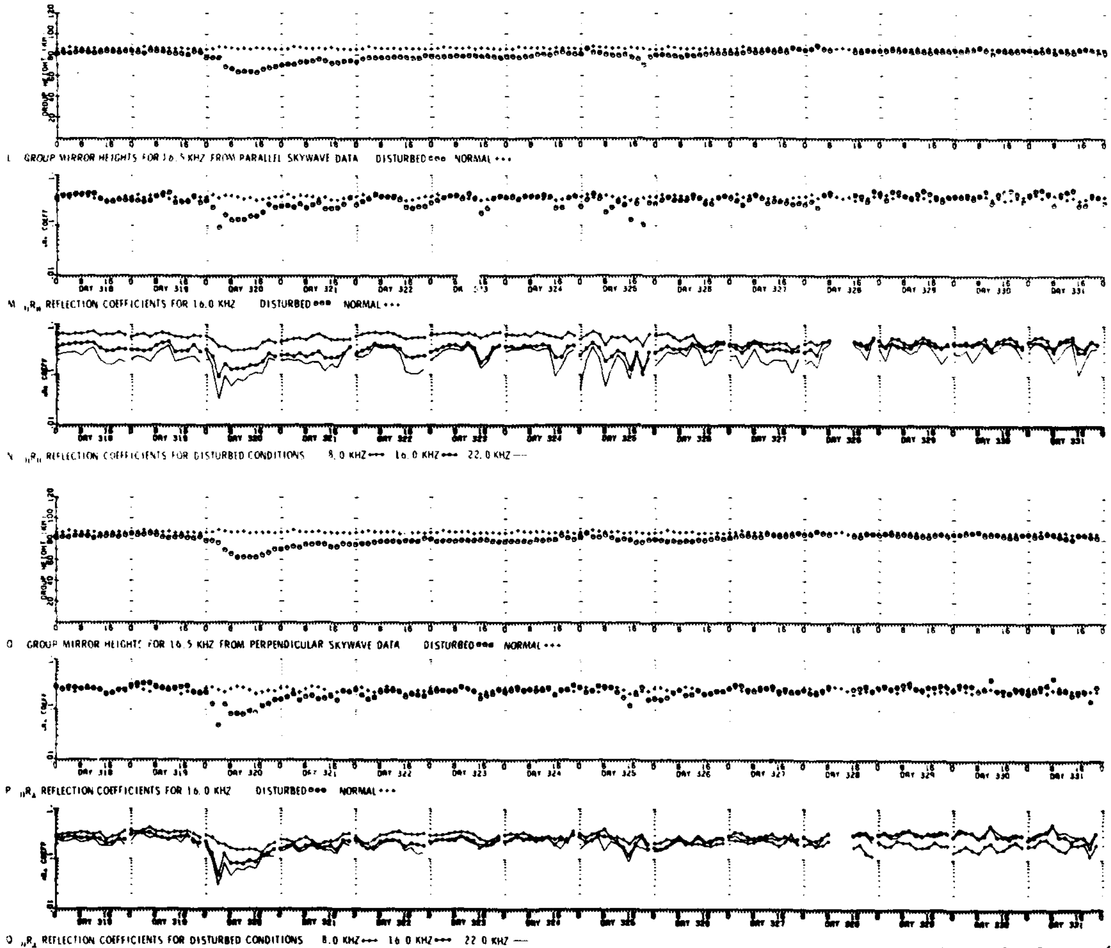


Figure 14. VLF/LF Ionospheric Reflectivity Data for 16 November 1979 (DAY 320) Solar Particle Event (contd)

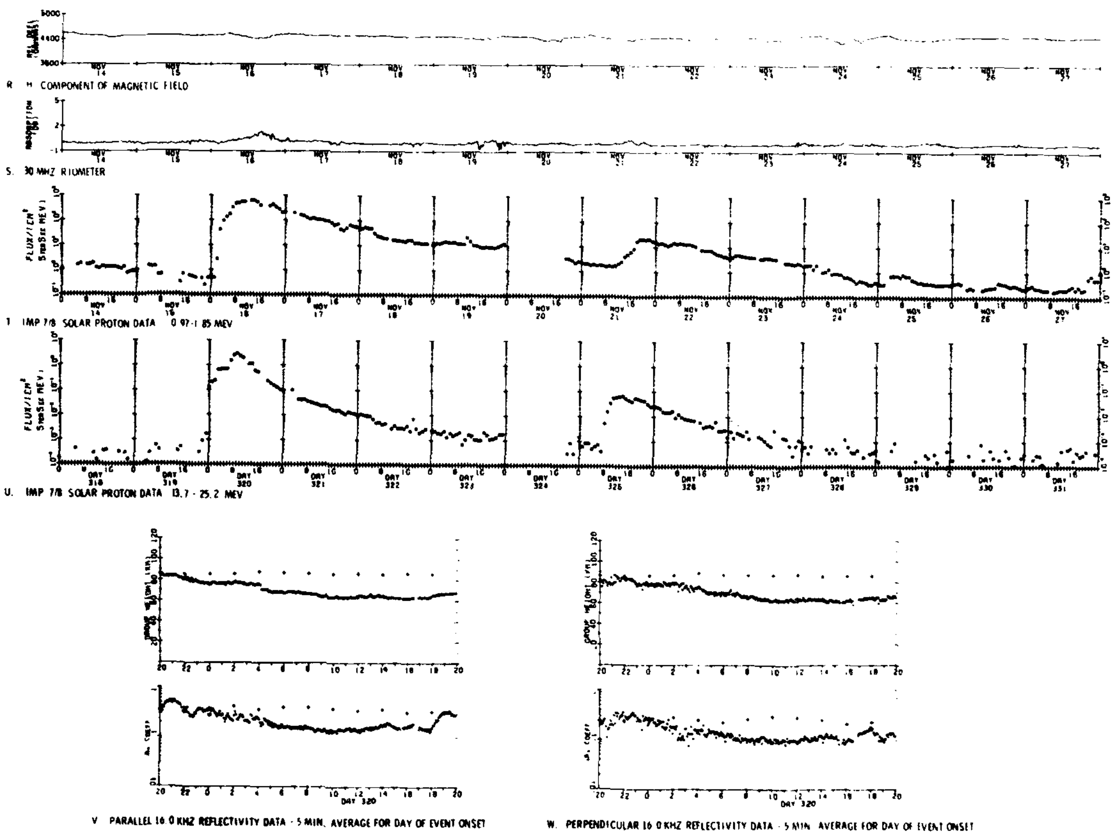


Figure 14. VLF/LF Ionospheric Reflectivity Data for 16 November 1979 (DAY 320) Solar Particle Event (contd

23 April 1979 Low Energy Solar Proton Event

DAY 113

Report Figure: 15

Start of Ionospheric Disturbance:	23 UT
Time of Maximum 0.9-2 MeV Proton Flux:	25 April 0500 UT
Maximum Flux:	900 particles/cm^2 sec sr MeV
Length of Particle Event:	5 days
Lowest 16 kHz Reflection Height:	69 km
30 MHz Riometer Absorption:	0.5 dB
Solar Zenith Angle Range:	65° - 93°
Illumination Conditions:	Daytime

This was a low energy event. The 20 MeV protons stayed below about 10^{-3} particles/cm^2 sec sr MeV throughout the entire period. The 1 MeV proton flux reached a maximum of about 900 particles/cm^2 sec sr MeV. A comparison of the parallel and perpendicular reflection height curves (parts L and O) with the low energy particle flux (part T) indicates that the heights were constant at about 70 km during the period when the particle count was above 100. The abrupt recove y of the reflection heights at about 800 UT on 25 April (DAY 115) was coincident with the sudden drop in the particle flux below 100 particles/cm^2 sec sr MeV.

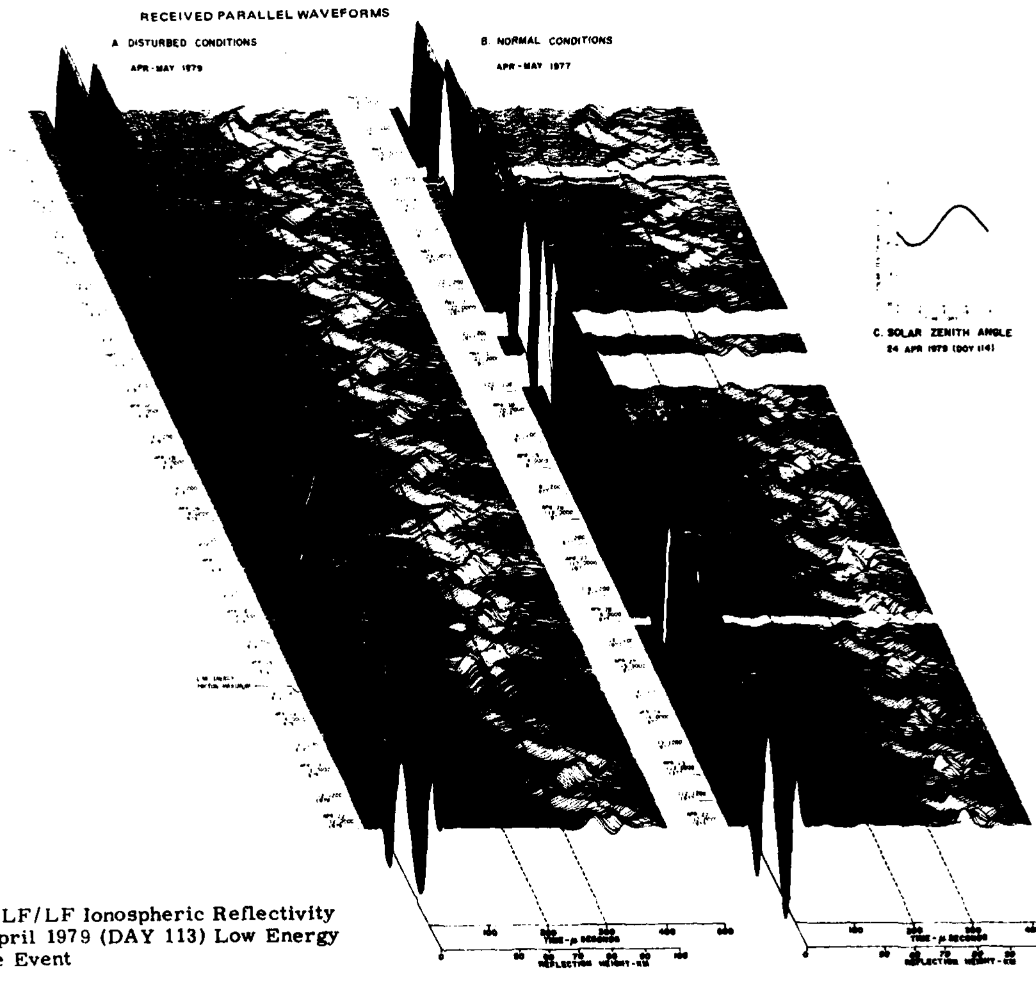


Figure 15. VLF/LF Ionospheric Reflectivity Data for 23 April 1979 (DAY 113) Low Energy Solar Particle Event

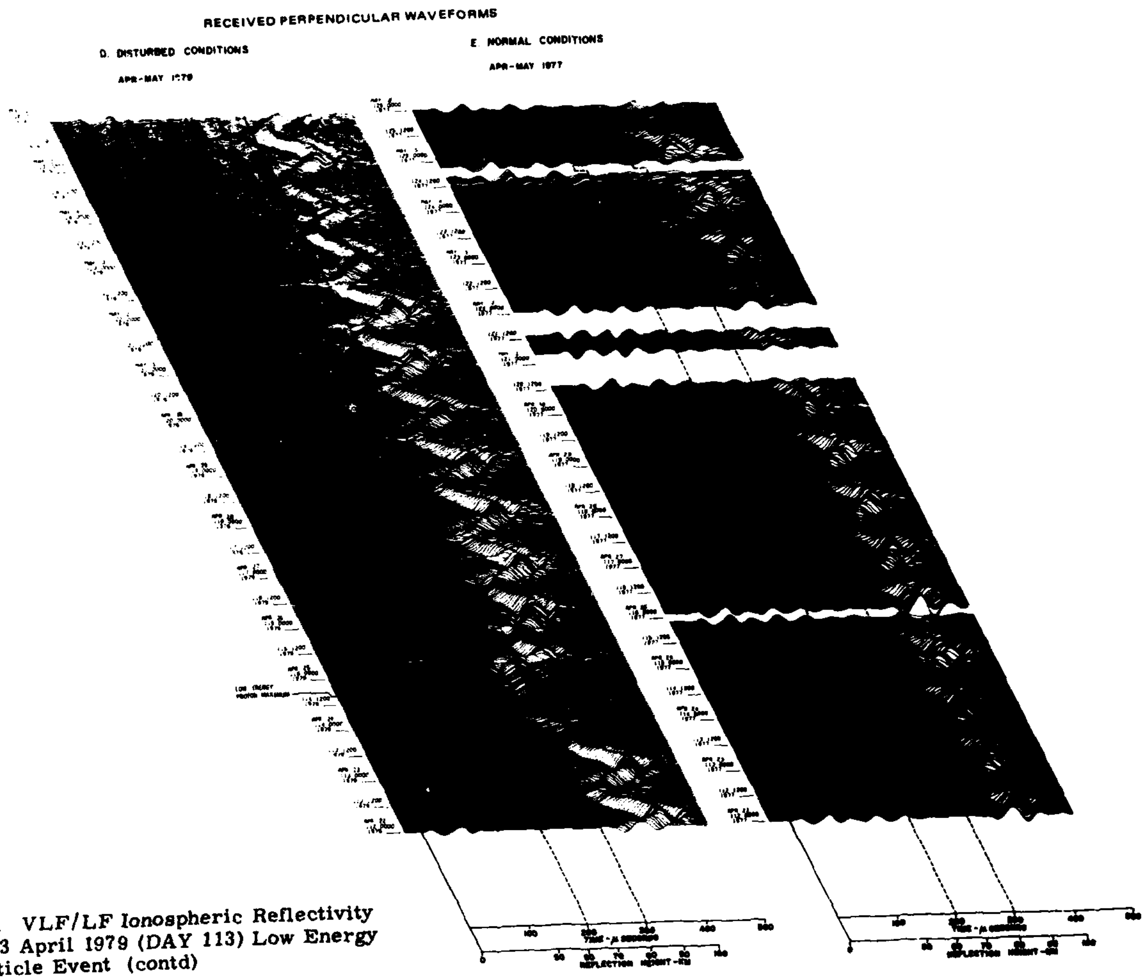


Figure 15. VLF/LF Ionospheric Reflectivity Data for 23 April 1979 (DAY 113) Low Energy Solar Particle Event (contd)

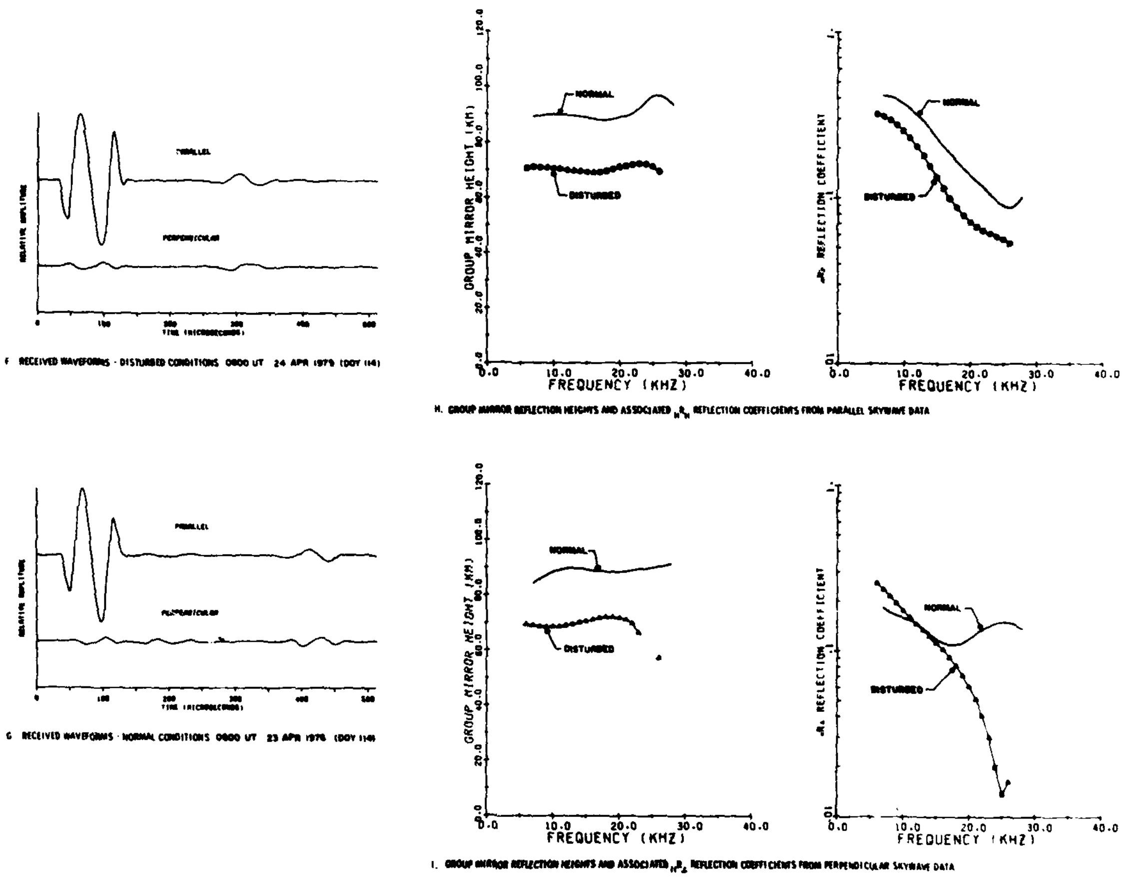
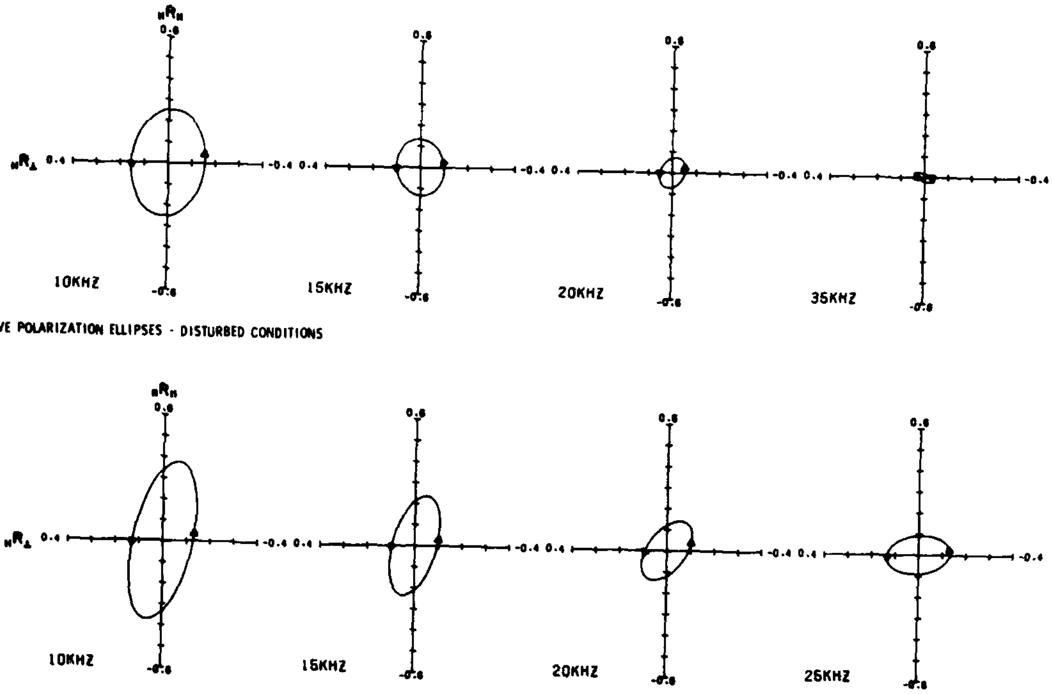


Figure 15. VLF/LF Ionospheric Reflectivity Data for 23 April 1979 (DAY 113) Low Energy Solar Particle Event (contd)



J. SKYWAVE POLARIZATION ELLIPSES - DISTURBED CONDITIONS

K. SKYWAVE POLARIZATION ELLIPSES - NORMAL CONDITIONS

Figure 15. VLF/LF Ionospheric Reflectivity Data for 23 April 1979 (DAY 113) Low Energy Solar Particle Event (contd)

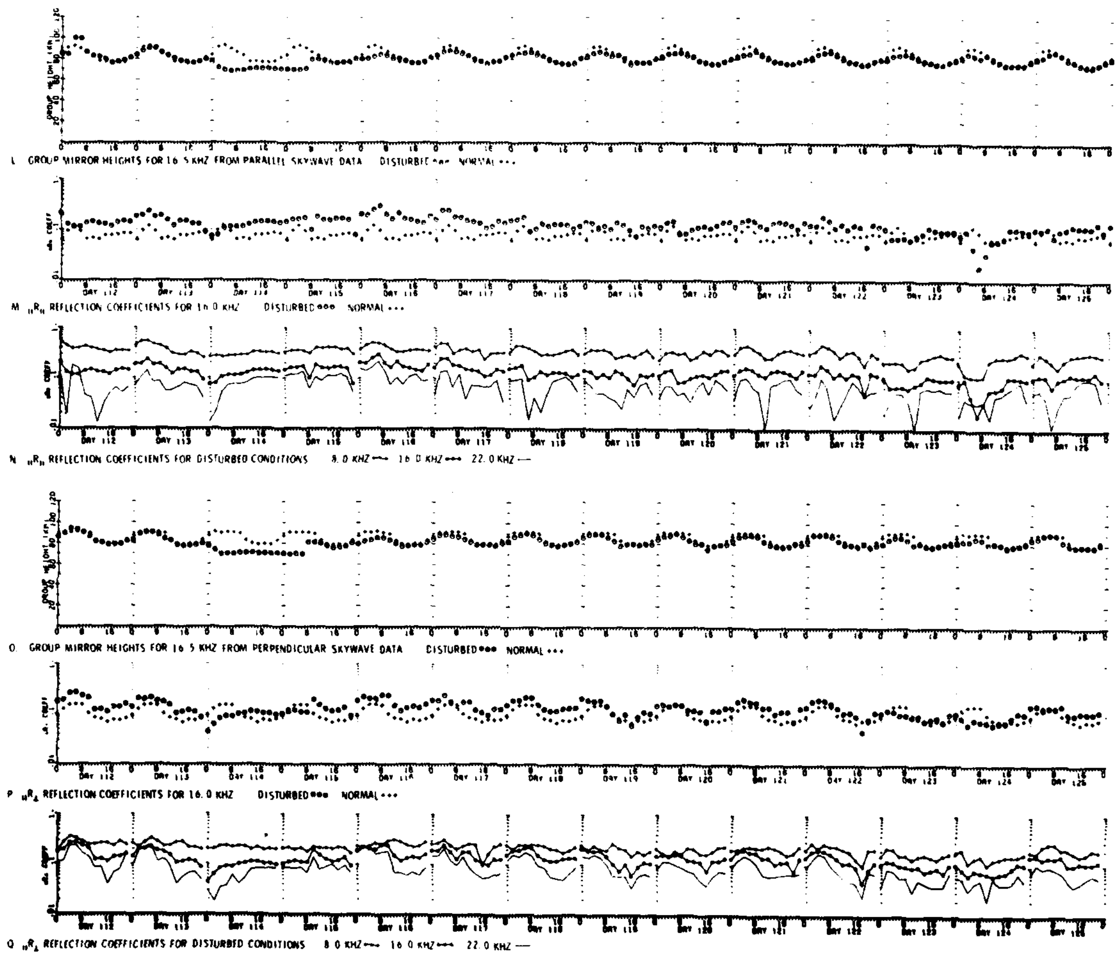


Figure 15. VLF/LF Ionospheric Reflectivity Data for 23 April 1979 (DAY 113) Low Energy Solar Particle Event (contd)

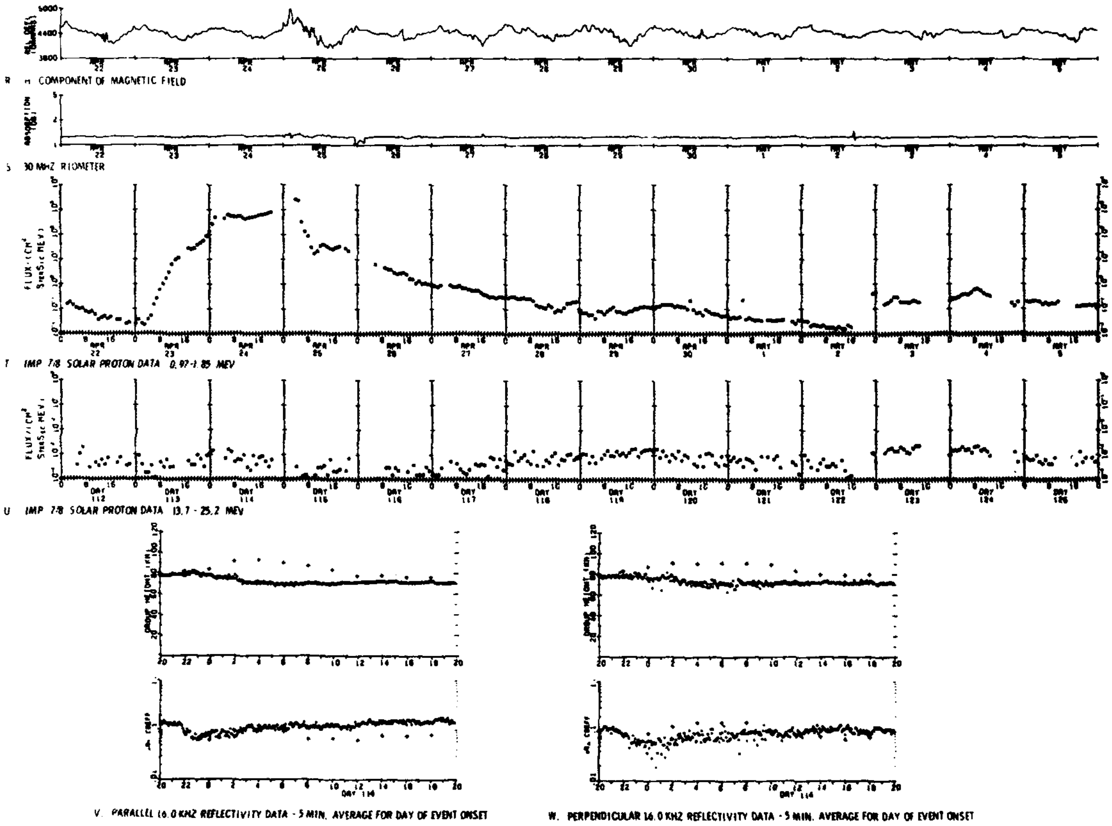


Figure 15. VLF/LF Ionospheric Reflectivity Data for 23 April 1979 (DAY 113) Low Energy Solar Particle Event *(contd)*

27 May 1979 Low Energy Solar Proton Events

DAY	147
Report Figure:	16
Start of Ionospheric Disturbance:	0100 UT
Time of Maximum 0.9-1.8 MeV Proton Flux:	27 May 0300 UT
Maximum Flux:	200 particles/cm^2 sec sr MeV
Length of Particle Event:	9 days
Lowest 16 kHz Reflection Height:	69 km
30 MHz Riometer Absorption:	< 0.5 dB
Solar Zenith Angle Range:	55° - 89°
Illumination Conditions:	Daytime

This was primarily a low energy event. The 13-25 MeV protons reached only $6 \times 10^{-3}/cm^2$ sec sr MeV (below event criterion). The 0.9 - 1.8 MeV protons reached a maximum of about 200/cm^2 sec sr MeV. As with other daytime events no diurnal height variation is seen during the event. The reflection coefficients (parts N and Q) showed a decrease at event onset and then showed less variation than before and after the event. As is typically seen during daytime events the 22 kHz reflection coefficients dropped to a low value during the latter part of the event recovery. This is not associated with increased particle fluxes and may be caused by interference between two layers in the ionosphere. The effects of the event lasted until 2 June (DAY 152).

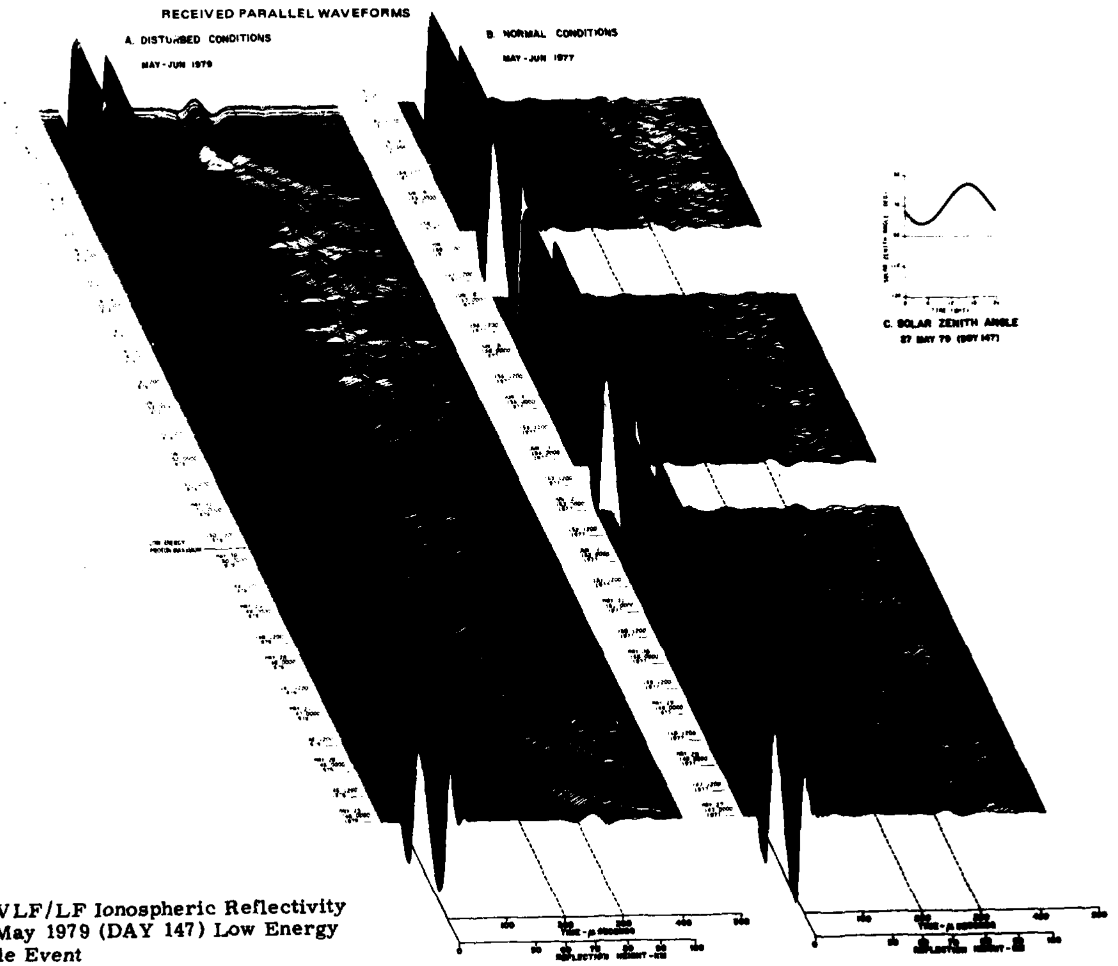


Figure 18. VLF/LF Ionospheric Reflectivity Data for 27 May 1979 (DAY 147) Low Energy Solar Particle Event

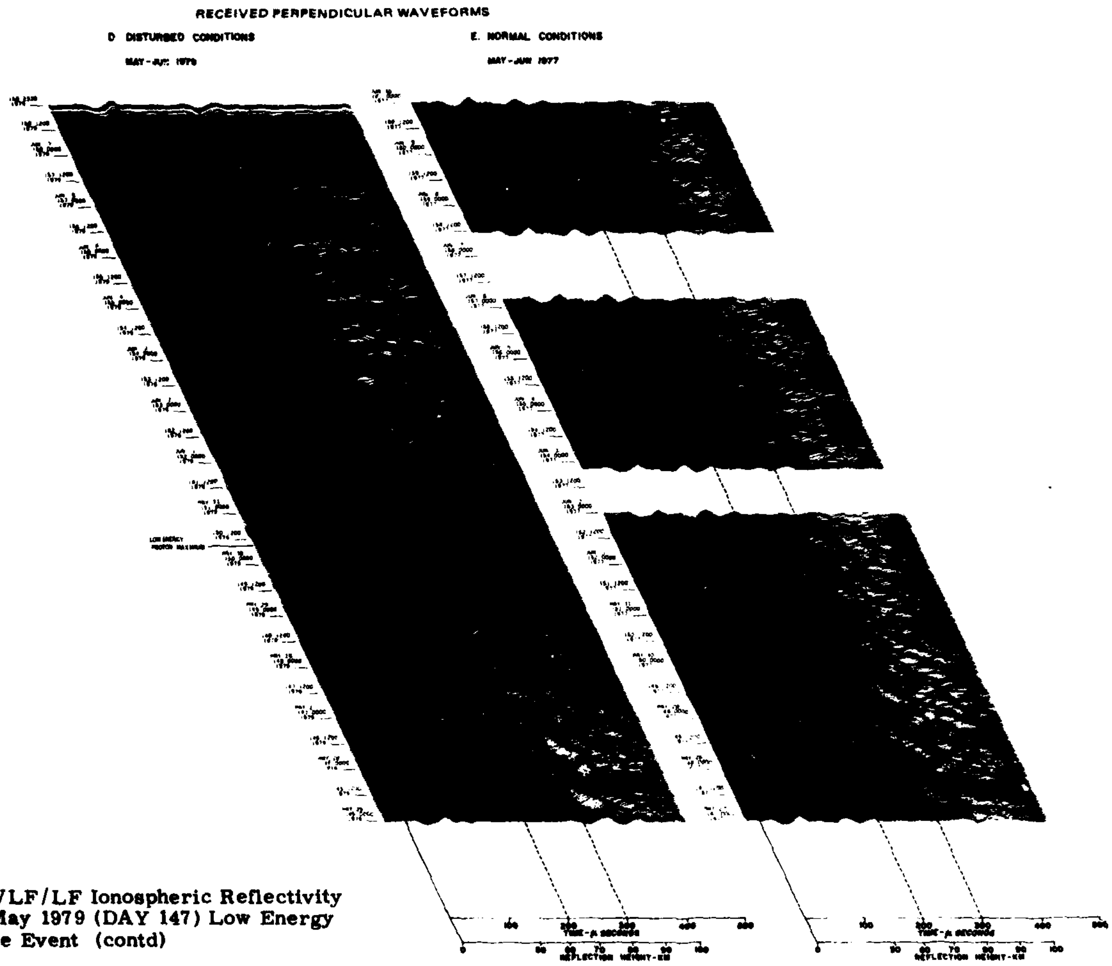


Figure 16. VLF/LF Ionospheric Reflectivity Data for 27 May 1979 (DAY 147) Low Energy Solar Particle Event (contd)

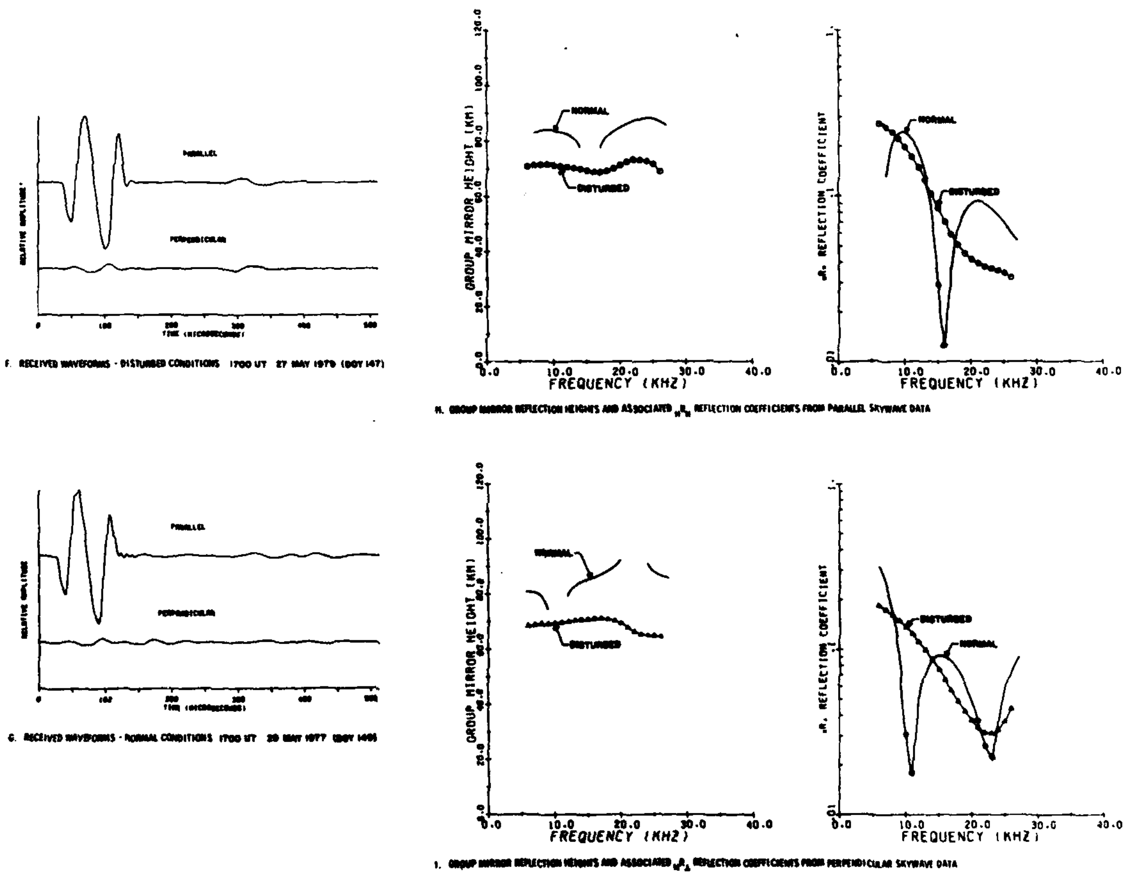
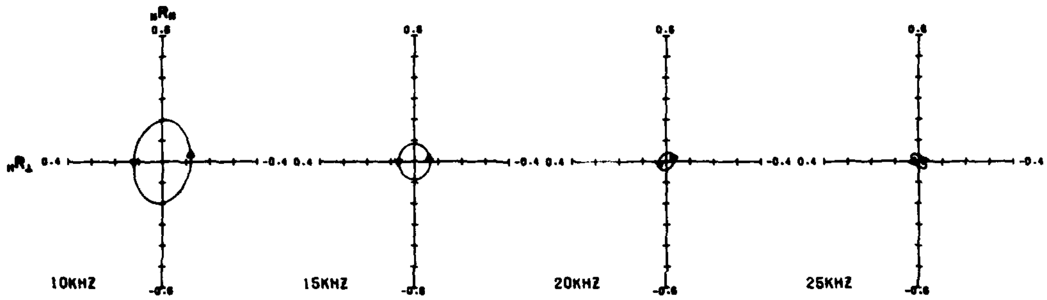
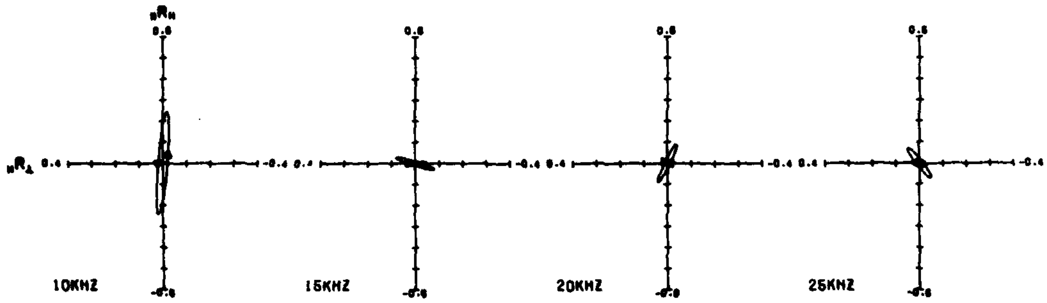


Figure 16. VLF/LF Ionospheric Reflectivity Data for 27 May 1979 (DAY 147) Low Energy Solar Particle Event (contd)



J. SKYWAVE POLARIZATION ELLIPSES - DISTURBED CONDITIONS



K. SKYWAVE POLARIZATION ELLIPSES - NORMAL CONDITIONS

Figure 16. VLF/LF Ionospheric Reflectivity Data for 27 May 1979 (DAY 147) Low Energy Solar Particle Event (contd)

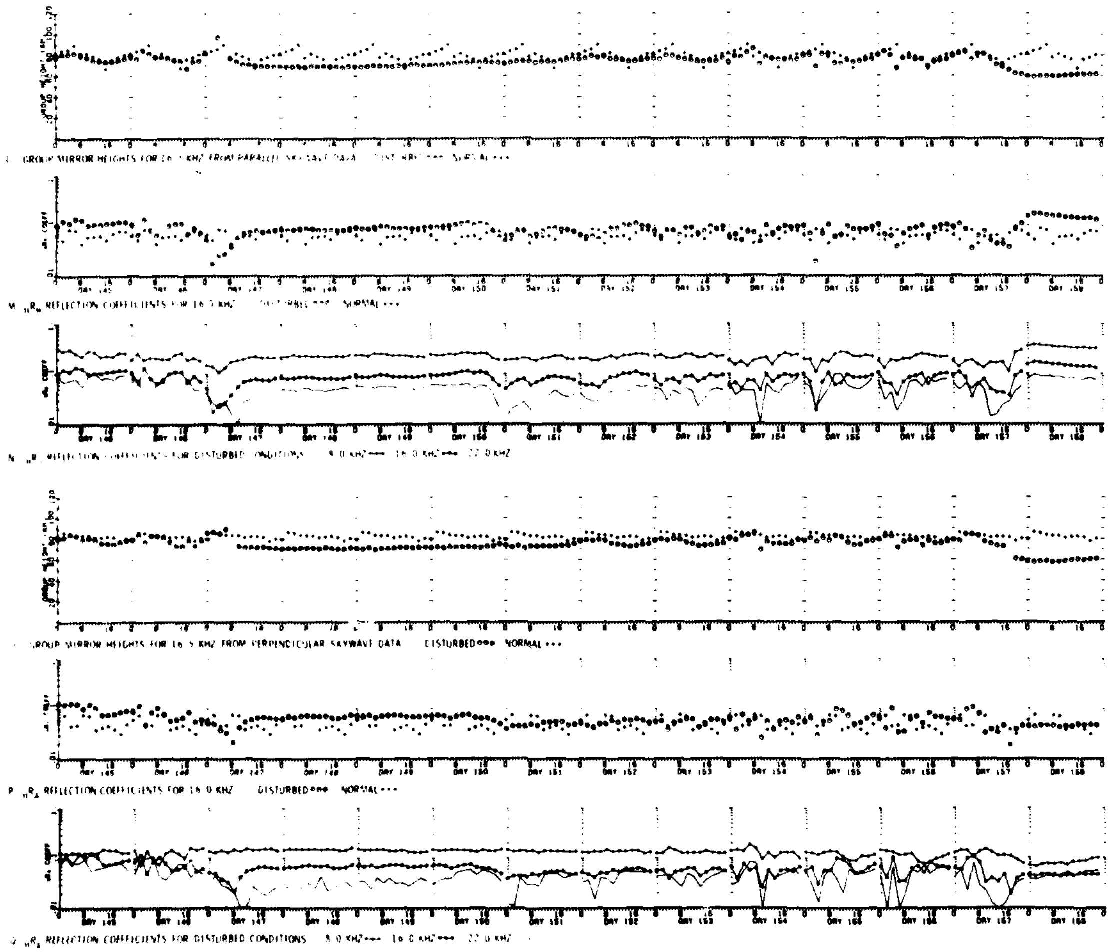


Figure 16. VLF/LF Ionospheric Reflectivity Data for 27 May 1979 (DAY 147) Low Energy Solar Particle Event (contd)

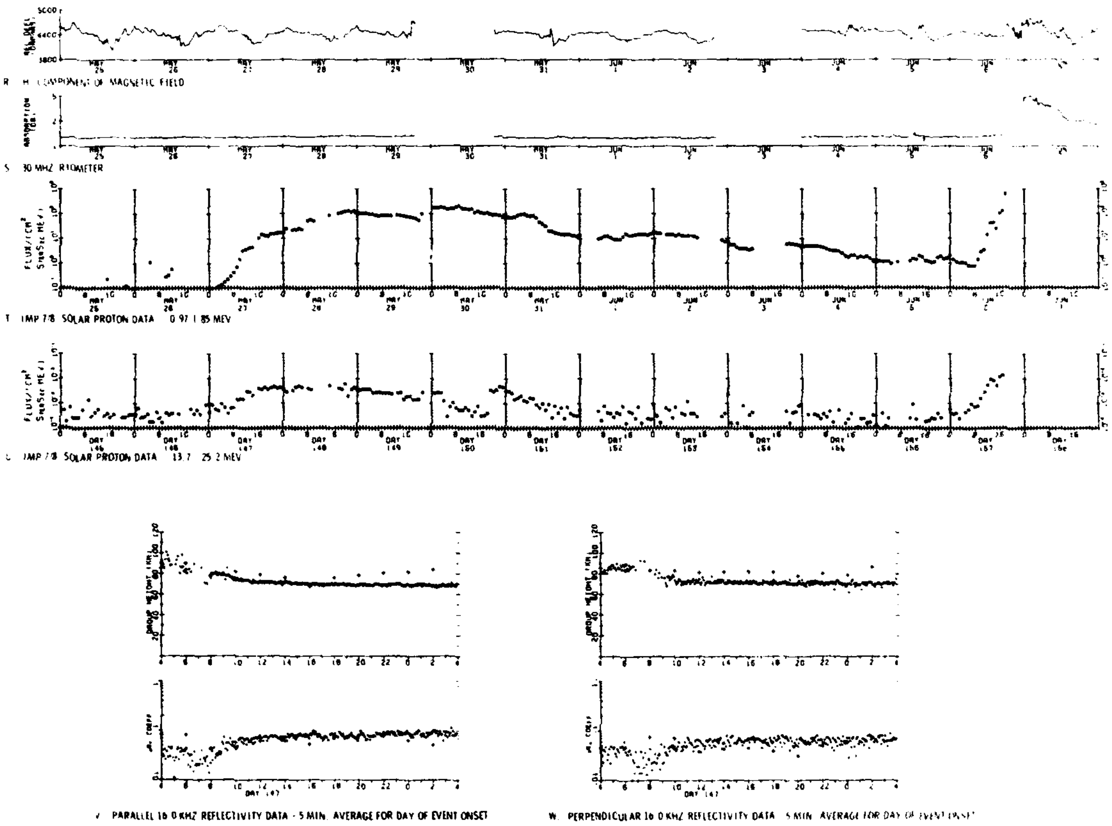


Figure 16. VLF/LF Ionospheric Reflectivity Data for 27 May 1979 (DAY 147) Low Energy Solar Particle Event (contd)

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